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THE PROBLEM OF THE ANORTHOSITES AND OTHER MONOMINERAL IGNEOUS ROCKS

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The story of monomineral igneous rocks, which occupy today such a prominent place in the problems of petrogenesis, may be outlined in a few words as follows. Formerly no special attention was paid to these rocks. When "simple" rocks were considered sediments, the monomineral silicate rocks were thought to belong to the sedimentary or the metamorphic series. That was, for instance, the case of the Canadian and other North American anorthosites, and Adams[1] was obliged to argue, in 1893, for their igneous origin. Several years afterward the present writer considered the monomineral igneous rocks as derived from those extremely pure magmas, unable to split farther, toward which the differentiation of a complex magma tends. From my own and Brögger's point of view on magmas as solutions of minerals, where the differentiation consists not in the wandering of separate oxids, as was then maintained by Iddings, but in the transfer of those groups of oxids and silica which correspond to the minerals of the future rock, I was led to admit that every igneous rock had its feld-

[1] F. Adams, "Über das Norian oder Ober-Laurentian von Canada," *Neues Jahrb. f. Miner.*, Beil.-Bd. VIII (1893), p. 419.

spathic facies.[1] Vogt referred the formation of the monomineral rocks to the eutectic scheme, and contrasted the "anchimonomineral" rocks with the "anchieutectic." Daly applied his view on gravitative differentiation and his eclectic theory of the origin of the igneous rocks (which is essentially, as he himself states in his admirable and highly suggestive book, *Igneous Rocks and Their Origin*, a further development of my syntectical-liquational theory) to monomineral rocks. In the conceptions of Vogt, Daly, and the writer the formation of monomineral rocks is intimately connected with magmatic differentiation in the liquid state. Bowen, on the contrary, on the basis of his important and suggestive laboratory experiments, attributed the formation of the monomineral rocks to differentiation by crystallization. He considers these rocks as resulting from a gravitative accumulation of crystals in the early stages of the crystallization of a basaltic magma. The essential difference between Vogt, Daly, and myself on the one side, and Bowen on the other, is that according to us the monomineral rocks existed as such in the liquid state, while Bowen does not admit the existence of a monomineral rock in the liquid state. He considers such rocks only as gravitational accumulations of solid crystals during the crystallization of a basaltic magma.[2] For the anorthosites of southwest Baikal, Switalsky presented a third view. He thought that all of these rocks ". . . . originated from a liquid mass," but they were formed from sedimentary materials; the anorthosites, granites, monzonites, and gabbros by fusion of the sediments, and the crystalline schists by recrystallization in the solid state.[3]

The peculiar characteristics of the anorthosites are the enormous dimensions of certain anorthosite bodies, their presence exclusively among plutonic rocks and the absence of their effusive equivalents, the frequently occurring extreme coarseness of grain,

[1] F. Loewinson-Lessing, "Kritische Beiträge zur Systematik der Eruptivgesteine. IV. Ueber monotektische (ungemischte) Magmen," *Tscherm. Min. Mitt.*, XX, p. 15.

[2] N. L. Bowen, "The Later Stages of the Evolution of the Igneous Rocks," *Jour. Geol.*, Suppl. to Vol. XXIII (1915); "The Problem of the Anorthosites," *ibid.*, Vol. XXV (1919), p. 209.

[3] N. Switalsky, "The Anorthosite Rocks and the Pyroxenic Crystalline Schists of the Southwest Baikal Region," *Bull. Com. Geol. de Russie* (1915), p. 999.

and their ancient age. The Canadian, North American, South Russian(?), and African(?) anorthosites are of pre-Cambrian age, and the Norwegian are Silurian. Of course the question of age is not to be valued too highly. New data must be expected, for we must not forget that granites were formerly also considered as exclusively pre-Cambrian, while now we know not only Paleozoic but also Mesozoic, and even Cenozoic representatives of this group.

During recent years especial attention has been paid to gravitational differentiation, a phenomenon produced by the difference between the densities of the crystallizing minerals and the still liquid portion of the magma. This conception has been especially favored by Bowen and Daly.[1]

The idea of gravitational differentiation is not new, having been introduced many years ago by Darwin. I have myself made use of this idea and have applied my own considerations and qualitative experiments to it. As before, I continue to consider gravitational distribution of phenocrysts as a factor in the mechanism of crystallization and differentiation of igneous rocks and in the formation of magmatic ore bodies; but I must confess that sometimes the significance of this factor is valued much too highly, and the limits of its application are made too broad. In order to prove this assertion and to show to what degree this factor is considered applicable by the writer, let us see briefly how different authors have applied the factor of gravitative adjustment of crystals to the theory of differentiation.

According to Sartorius von Waltershausen, even during the period of the formation of the earth's crust the liquid mass was split into layers of different densities, so that the deeper layers consisted of denser liquid masses and the upper of the lighter ones. The different volcanic centers were fed by different layers. This general speculative conception is rather far from the phenomenon of differentiation and cannot explain in a satisfactory way the diversity of volcanoes and lavas. It is useless to enter here into further details of this hypothesis.

Gouy and Chapéron expressed the idea that in a deep layer of a solution there must be a gravitational concentration of the dis-

[1] R. Daly, *Igneous Rocks and Their Origin*, 1914.

solved salts in the lower parts. Direct experiments are wanting; the oceans do not seem to support this assertion. Should this phenomenon really exist, it would assume long periods of rest in the magma, undisturbed by convectional and other currents. Let us not further insist upon this hypothesis.

Let us now examine the remaining application of gravitative adjustment in the liquid magma, namely the gravitational distribution of the minerals during crystallization. Here again we may assume two cases: (1) the distribution, according to their densities of those minerals which are the definite components of the growing igneous rocks, i.e., the components corresponding to a full equilibrium; (2) the sinking or floating of the first products of crystallization which may issue from the dissociation of the final products. These minerals correspond to an unstable and temporary equilibrium. If they are not removed by sinking or floating, they are redissolved and replaced by those definite components from whose dissociation they were derived. This is Bowen's view. It is necessary to analyze each of these two cases separately.

1. Examples of such a gravitational distribution of phenocrysts in lavas, diabases, and nephelite syenites are well known, for instance, two facies of the Vesuvius lavas, one rich in leucite, the other in augite; the more pyroxenic and the more feldspathic facies of the Olonetz (Petrosawodsk) diabase studied by the author;[1] and the nephelite-sodalite- and nephelite-eudalite-syenites of Ussing. It is only natural to attribute to this process the melanocratic facies of certain laccoliths or intrusive sheets, the granophyric upper layer of certain gabbors, the variolitic structure of certain diabase masses, and so forth. Gravitational differentiation understood in this sense certainly really exists. More than that, I think that Schweig is right in assuming that the early crystallized minerals, sinking into the deeper parts of the magma where the temperature may be higher, can be dissolved. In this way certain components of the magma may be transported by the aid of a temporary solid phase into the deeper horizons, and finally there may result two different layers and the formation of a batholith or a laccolith con-

[1] F. Loewinson-Lessing, "The Diabase Formation of Olonetz," *Trav. d. l. Soc. d Natur. St. Petersb.*, 1888.

sisting of two different rocks. In the same way differentiation may be induced by the floating of the lighter crystals, as well during the crystallization of a liquid magma as in the process of anatexis. An old experiment of Sorby[1] is very instructive. When he fused a hornblende granite from Mount Sorrel he observed that the hornblende melted first and some of the feldspar and quartz floated.

The formation in this way of a small anorthositic or pyroxenitic facies in a gabbro body is easily conceivable. On the other hand, the formation of a large anorthosite body requires rather that the sinking of pyroxene crystals should be accompanied by their resolution in the deeper parts, until the magma is finally almost completely separated into anorthosite and pyroxenite with gabbro between them.

2. According to Bowen the magma does not contain definite minerals as these are dissociated. The first crystallized minerals, being only temporary products of this dissociation, are again dissolved and disappear if the period of crystallization is sufficiently quiet and long. So, for instance, in a magma corresponding to a certain mixture of diopside and labradorite, olivine is formed at the beginning of crystallization, and in this way a certain quantity of free silica is produced. In the later stages of crystallization the olivine is again dissolved and, combining with the silica, crystallizes at last as diopside. But if the olivine, formed at the beginning, is eliminated by sinking, the magma might fully differentiate into an olivine rock, gabbro, syenite, or even granite. This conception is based on Bowen's experiments: chilling an enstatite melt demonstrated that at the beginning of crystallization olivine was formed; when crystallization was slowly brought to an end the olivine disappeared and the whole melt crystallized as clinoenstatite. It is quite certain (see Bowen's photographs) that olivine is really formed in these conditions from an enstatite melt and that it tends to concentrate in the lower parts of the crucible. But, in conceding this, we are nevertheless very far from concluding that this process is realized on a large scale in the earth's crust, and that a basaltic (gabbroid) magma will split into dunite, pyroxenite, gabbro, syenite, and granite. In order to support such a conclusion, we have to

[1] H. Sorby, *Proc. Geol. a. Polytechn. Soc. W. Yorkshire*, Vol. IV (1863), p. 302.

admit that the olivine, which is formed at the beginning of crystallization, really sinks, that this sinking is not counterbalanced by currents and movements of the magma, that the sunken crystals are not dissolved, that the deeper horizons of the magma have not a higher temperature, that the crystals sink to the bottom, that there is a bottom, that the crystallization is going on very fast, and so on.

And even if all these suppositions can be confirmed, the result of such a differentiation would be very small, as will be shown below by a series of calculations. Those minerals which can be fixed by chilling do not correspond to the final equilibrium, as is illustrated by certain alloys of metals, which when chilled show components and structures not formed in these alloys when normally crystallized. Rankin has also found in the system CaO–Al_2O_3–SiO_2 combinations which do not occur in natural rocks, but no one would therefore conclude that these combinations must also occur in the igneous rocks. The conditions of crystallization, the rate of cooling, and the admixtures are evidently different in the two cases. Since the relatively simple mixtures of chemically pure components used in the laboratory and the complex natural magmas are essentially different, deductions from laboratory experiments with simple mixtures should be applied very cautiously and with certain restrictions to the very complex natural magmas. So, for instance Bowen states several times that spinels must crystallize from a basaltic magma, but we know that basalts do not contain spinels, neither is there clinoenstatite in the igneous rocks. The conditions of crystallization of a simplified "haplobasalt" and a natural basalt are different. Not only is the composition of the latter much more complex, but the gaseous components of the magma, the mineralizers, those ingredients whose importance is now so often noted, must be considered. Experimental laboratory work is certainly very important for the problems of petrogenesis, but we must not forget that our experiments are performed with simplified mixtures and in simplified conditions. Let us not repeat the mistake of Mohr who affirmed that a simple experiment in a crucible was sufficient to refute all the theories of the plutonists. Let us continue the experiments with simple mixtures of chemically pure compounds,

but let us, at the same time, study the crystallization of melted mixtures of natural minerals and of fused igneous rocks.

Bowen gives two points as special evidence for gravitational differentiation: (1) those intrustive sheets whose lower part consists of gabbro (diabase) and the upper of granite (granophyre); (2) the connection of nephelite syenites with granites (he admits that the former overlie the latter).

1. Examples of the first case are well known. The fact itself is beyond doubt, but the question lies in its interpretation. Every author of a general theory of differentiation makes use of these facts to support his own views, and it is therefore easy to see how subjective the interpretations become. A very instructive example is afforded by the sills of the Purcell Mountains. While for Bowen they are a confirmation of his view that the granite did not come from a distinct magma but was derived from the basaltic magma which is the one and only mother-magma of all igneous rocks, for Daly the same intrusive bodies illustrate his eclectic hypothesis, of a syntexis of the basaltic magma with quartzite, followed by differentiation. Bowen asserts that the granites are everywhere underlain by granodiorites, diorites, and gabbros, and that these rocks can be seen wherever the granites are cut through by denudation. He says further that the thickness of the granite layer does not exceed from 10 per cent to 15 per cent of the whole intrusive body. Where are the proofs for such assertions, and how can they be brought into agreement with the fact that the dimensions of granite bodies exceed by far those of other intrusive rocks?

2. The frequent, or perhaps even constant (?), association of nephelite syenites with granites has been mentioned by Daly, and this is really a very frequent combination, but there are no proofs that nephelite syenites always overlie granites.

As already mentioned, the theory of the origin of the anorthosites (and other monomineral igneous rocks) by the accumulation of solid crystals, and the denial of their existence in the liquid state, is founded on the following geological and petrographical data: (1) protoclastic structure, (2) lack of dikes, (3) lack of effusive equivalents, (4) absence of mineralizers, (5) the forms of the rock bodies and their stratigraphical relations.

Let us examine each of these considerations separately.

1. Protoclastic structure is not characteristic of all anorthosites (see those of Kiev and the Baikal). This structure can be explained in certain cases by the action of mineralizers (cf. my considerations on the origin and the effect of zoisite in the anorthosites of Syysertsk in the Oural Mountains).[1] Furthermore protoclastic structure is wanting in pyroxenites and dunites, these latter being characterized by a special structure, indicative of the process I call *magmatic autocatalysis*.

2. Should it really be proved that the monomineral igneous rocks do not occur in dikes, this fact by itself would not be a sufficient proof against their existence in the liquid state. The great viscosity of such simple magmas is a sufficient cause for their being incapable of forming small intrusions. But the absence of dikes in the group of the monomineral rocks is not at all an irrefutable statement, for pyroxenites and dunites often occur in this form. Rosenbusch and Daly even assume that the dike form is usual for pyroxenites. Of course Rosenbusch (*Elemente der Gesteinslehre*) is not correct in assuming that pyroxenites and peridotites occur only in dikes; the large intrusive masses of pyroxenites in the Blue Mountains near Barantcha (Oural),[2] the pyroxenites and dunites of the Denejkin Kamen,[3] and other localities in the Oural Mountains are in contradiction with this assertion.

Certain feldspathic rocks occur also in the dike form, for example, the albitites. In the region of the Canadian anorthosites Adams cites dikes. On the other hand, we may ask: Do gabbros (except beerbachite and gabbroporphyrite) or nephelite syenite often occur in this form?

[1] F. Loewinson-Lessing, "On the Most Southern Deposit of Platinum in the Oural," *Annales de l'Inst. Polytechn. St. Petersb.*, Vol. XIII (1910).

[2] Th. Tschernyschew, "Le Chemin de fer dans les Limites les districts miniers de Taguil et de Goroblagadat," *Guide des Excurs., Congr. Geol. St. Petersburg*, 1897.
F. Loewinson-Lessing, "A New Locality of Platinum Deposits (in the Blue Mountains, near Barantcha, Oural)." *Annals l'Inst. Polytechn. St. Petersburg.* 1909. Vol. XI.

[3] F. Loewinson-Lessing, "Geologische Skizze der Besitzung Jushno-Saasersk und des Berges Denejkin Kamen im nördl. Ural." *Trav. d.l. Soc.d. Natur. St. Petersburg*, 1900. In this monograph I have described and figured a series of very manifold banded gabbros. Grout does not cite me in his paper on banded structures as he evidently does not know my book.

3. The lack of effusive equivalents of the anorthosites and other monomineral igneous rocks is quite a natural consequence of their great viscosity and their consequent inability to reach the earth's surface in the liquid state. I have previously pointed to that conclusion. Bowen refutes these considerations but without any arguments.

4. The mineralizers, and those minerals which are to be referred to their action, are in general very rare in basic rocks. In many gabbros they are quite absent. Meantime we may remember that the zoisite mentioned above in certain anorthosites from the Oural, and the primary serpentinization of the dunites are to be referred to the action of mineralizers.

5. The stratigraphical relations of the anorthosites argue for their igneous and not for their sedimentary or metamorphic origin. Their igneous origin is demonstrated by their intimate connection with the rocks of the gabbro group and through these with syenites by the anorthositic (and pyroxenitic) facies of the banded gabbros, by several features illustrating their intrusion into the neighboring rocks, and by contact metamorphic actions, as for instance, around the big Canadian anorthosite bodies. But it is not enough to state their intrusive origin in such general terms, for there are in the geological literature two different interpretations of the anorthosites, both, as already stated, relying on the theory of intrusion. It is necessary, therefore, to analyze more closely the stratigraphical relations in order to see whether they support the views of most writers or those of Bowen.

Adams[1] states with reference to the Morin laccolith: "Fassen wir noch einmal zusammen, so haben wir in diesem Gebiet eine grosse intrusive Masse von Anorthosit, welche die Grenville Stufe durchbricht, grosse Gneissblöcke einschliesst, Apophysen in die umgebenden Gesteine entsendet und an vielen Stellen, wie es scheint, von einem eigenartigen Contactproduct begleitet wird." Especially important seem to me the contact phenomena and the small intrusive sheets of anorthosite in the gneiss. Daly (p. 331) agrees with Adams, and says, in reference to the Morin laccolith and several intrusive bodies of gabbro and anorthosite in the Haliburton-

[1] F. Adams, *op. cit.*, p. 433.

Hastings region, that the zones of contact coincide with the cleavage surfaces of the gneisses, limestones, and other rocks, and since the cleavage is parallel to the stratification planes, the metamorphic zones argue for the laccolithic and not batholithic character of these bodies. Bowen's mention of the local occurrence of perthitic feldspar is hardly an argument for the hypothesis that the anorthosite was covered by syenite, that both are derived from a basaltic magma, and that the anorthosite is a sheetlike mass, like the intrusive mass of the Adirondacks. Of course, in stating that the Adirondak massive is a sheetlike body consisting of anorthosite at the bottom and syenite at the top (both rocks resulting from a differentiation *in situ* of a basaltic mother-magma), Bowen is cautious and considers this interpretation a conditional one: "And again, the writer's interpretation of the igneous mass as sheetlike is offered merely because of the difficulties of picturing the general relation otherwise."[1] At the same time he mentions xenoliths of Grenville rock in the anorthosite, a feature suggesting the intrusive character of the anorthosites, and gives examples of assimilation of the covering rock by the syenite, etc. All these data show that the stratigraphical features are not conclusive for Bowen's views. And furthermore, it is rather doubtful whether the accumulation of labradorite crystals at the bottom and the separation of a syenitic liquid at the top do agree with their respective densities at the temperatures existing during the stage of crystallization when this differentiation was going on.

The connection of anorthosite with syenites in the Morin and Andirondack bodies is conspicuous, but their genetic relations are not sufficiently evident. Cushing considers the Adirondack syenite as younger than the anorthosite, the syenite sending apophyses into the anorthosite—a statement decidedly invalidating Bowen's interpretations.

The other labradorite regions do not afford such stratigraphical data as could be made use of for sustaining this or that interpretation. I could find such data neither in Kolderup's[2] writings on the

[1] N. L. Bowen, "The Problem of the Anorthosites," *Jour. Geol.*, Vol. XXV (1917), p. 226.

[2] K. Kolderup, "Die Labradorfelse des westlichen Norwegens. Ia, II," *Bergens Mus. Aarbog*, Vol. I (1896; Vol. V (1903), No. 12.

Norwegian labradoritites, nor in Tarassenko's[1] monograph on the labradoritites of Kiev.

The problem of the anorthosites is not exhausted by an interpretation of the anorthositic bodies. There still remain the anorthositic bands in the banded gabbros of Scotland and the Denejkin Kamen (the latter evidently unknown to Bowen). To these bands the conception of an accumulation of solid crystals is evidently not applicable, and the feldspathic, pyroxenitic, and magnetitic (titanomagnetite), as well as the leucocratic and melanocratic bands, must without doubt be considered as produced by differentiation from the liquid state. The writer and Harker have spoken of liquid immiscibility; I have further advocated the possibility of liquation in consequence of assimilation; and we can invoke other constituents coming into the magma during the process of assimilation, or the absorption of gases that can produce insolubility of a certain component and be therefore the cause of its precipitation, like alcohol precipitating some substance form an aqueous solution. All of these suppositions are only conjectures. Experimental data are needed; but there are certainly data favoring the hypothesis of magmatic differentiation, and Bowen's hypothesis is not applicable to the banded gabbros.

In the Denejkin Kamen the ultrabasic rocks occur as small veins and dikes in the gabbro. Their solidification was subsequent to the consolidation of the gabbro and not the reverse as required by Bowen's scheme. In Quebec (Chibougamau) according to Daly, the hornblendite, pyroxenite and dunite cut the gabbro in dikes.

Vogt, as is well known, has applied the eutectic scheme to the interpretation of monomineral rocks. Bowen, on the contrary, considers this scheme as inapplicable to igneous rocks because of the widespread occurrence of solid solution. I think there is a misunderstanding. Solid solutions and isomorphism are confined to limited mineral groups, but the minerals of different groups, in spite of being solid solutions, may be in eutectic relations. Conceding to Bowen that it is not correct to speak of a eutectic mixture of diopside and plagioclase, since the different plagioclases have

[1] W. Tarassenko, "The Rocks of the Gabbro Family in the Radomysl and Shitomir Districts of the Governm. of Kiev," *Mem. Soc. Natur. Kijev.*, Vol. XV (1896), pp. 1–347.

different fusion points, we can certainly speak of diopside-labradorite (of a definite composition) eutectics, diopside-anorthite-eutectics, etc. In certain cases the eutectic scheme is doubtless to be upheld. For the rocks of granitoporphyric (holocrystalline-porphyritic) texture I consider the eutectic rule as the leading factor in the formation of phenocrysts. For instance, by measurements with the Hirschwald ocular I have found that in diorite-porphyrite the phenocrysts belong either to amphibole or to plagioclase depending upon the predominance of the one or the other respectively over a certain proportion, which is to be considered as the eutectic mixture, quite as with alloys of metals or salts.[1]

Finally we must not omit the paragenetic relations of the great anorthositic and pyroxenitic regions. The anorthosites of Canada, Norway, and southwest Russia are connected with gabbro, norites, and syenites. They belong to that type of the gabbro formation which is united by intermediate members with syenites, and which is not accompanied by pyroxenites and dunites. On the other side the pyroxenites (Oural, America) and dunite are connected with a more basic type of the gabbro group. In the Oural they are accompanied by various ultrabasic types. There may be a certain legality in these connections, but it certainly would be a forced explanation should we say that in the Oural formations the anorthosites were destroyed by denudation, and that in Canada, Kiev, etc., the denudation has not yet reached the pyroxenites.

In regard to the paragenetic relations it is not to be lost sight of that the pyroxenite and dunite occur in connection with gabbros which contain the same minerals; alkaline pyroxenites are connected with alkaline rocks, albitites, and andesine feldspatholites with dioritic rocks, and labradoritites with gabbros. It is shown by these peculiarities of paragenesis that the monomineral facies is always formed by those minerals which are the characteristic components of the corresponding mixed rock; that the differentiation proceeds by the transfer of these minerals, which crystallized from the original magma (Brögger and myself), and not by the transfer

[1] F. Loewinson-Lessing and S. Zemčujny, "Porphyrartige Struktur und Eutektik," *Verhandl. Russ. Miner. Ges.*, 1906. (Experiments with salts and metallographic photograms of them.)

of temporary minerals unstable during the later stages of the crystallization of such a magma.

Let us now make several calculations which will show that even if we lay aside all the foregoing considerations and take Bowen's viewpoint, it is impossible to expect such effective differentiation as is assumed by Bowen from his experiments. Bowen studied the crystallization of a gabbroic magma consisting of 50 per cent labradorite (Ab_1An_1) and 50 per cent diopside. We will examine a magma of nearly this composition but containing also magnetite, as it usually does.

Let us take two mixtures:

I. 6 parts diopside: molecular weight $216 \times 6 = 1296$, or 41.3 per cent (in molecular percentages).
2 parts labradorite: $804 \times 2 = 1608$, or 51.2 per cent.
1 part magnetite: 232, or 7.4 per cent.
(The sum of the molecular weights is 3156; the total of molecular percentages 99.9).

II. A similar mixture but containing less magnetite, namely,

	Per cent
Diopside	42.3
Labradorite	52.4
Magnetite	5

We begin with the second mixture and examine two cases:

a) If two-thirds of the enstatitic silicate of our magma splits into olivine and free silica there will remain a pyroxene 2 ($MgO \cdot 3\ CaO \cdot 4\ SiO_2$), and we will have olivine $2(2\ MgO \cdot SiO_2) + 2\ SiO_2$. The free silica will be combined with the Fe_3O_4, i.e., to 2 FeO, and consequently there will be no formation of quartz.

b) If we assume the improbable case that the whole mass of the magnesian metasilicate will split and the rest will be 6 $CaSiO_3$ there will be 3 $(2\ MgO \cdot SiO_2) + 3\ SiO_2$, and after the neutralization of 2 SiO_2 by the ferrous oxide the remaining free silica can give 1.91 per cent of quartz.

We take now the first mixture (I). In the same conditions as already stated, even if the whole mass of the magnesian metasilicate splits, there will be no free silica.

We can admit a third case (III), namely, a magma devoid of magnetite, or we may suppose that the free silica will not combine with the magnetite. This will give us SiO_2 3 or 5 per cent of free silica.

Therefore, even if we admit conditions most unnatural and most unfavorable for Bowen's critics, a basaltic magma will either give no free silica at all, or will give only such a small amount that at best we can expect the formation of a quartz gabbro, poor in quartz, but never of granite or quartz-diorite.

Besides this it ought to be noted that Bowen[1] considers clinoenstatite as the only stable form under conditions of slow crystallization. During slow cooling full equilibrium is established, and only under conditions of artificial chilling can the minerals of the incomplete equilibrium stage (forsterite, enstatite, cristobalite) be fixed. The conditions of crystallization of the intrusive magma are those bringing it to full equilibrium.

And again, Bowen[2] tells us that a mixture of 98 per cent $MgSiO^3$ and 2 per cent SiO^2 will give forsterite and silica; but if there is 2.5 per cent or 3 per cent of silica, enstatite will be formed—a statement invalidating all presumptions on the formation of olivine and free silica from a basaltic magma.

Let us now make another calculation based on the specific gravities. In Daly's *Igneous Rocks* (p. 202) we find the specific gravities of gabbro, syenite, quartz, diorite, and granite at the temperatures of 20° C., 1000° C., 1200° C., and 1300° C., in the solid state and when molten. The specific gravity of crystalline labradorite is 2.689; when molten to glass it shows an expansion of nearly 7 per cent—specific gravity 2.525. Heated to 1000°–1300°, if still solid, the increase of volume if only equal to 3 per cent, will give a specific gravity of 2.609. Now, comparing these figures with the specific gravity of the liquid gabbro it is easy to see that the labradorite will sink only in a gabbro with a specific gravity of 2.80 (if molten 2.57–2.53); in all other cases the labradorite will float, especially if we take into consideration that the average density of gabbro is 2.933–2.975. I can easily conceive that during the crystallization of a gabbroic magma there will be a tendency toward

[1] N. Bowen, *Amer. Jour. Sci.*, CLXXXVIII (1914), p. 237.

[2] *Amer. Jour. Sci.* (1914), p. 487.

the formation of a melanocratic facies in the lower part and a leucocratic in the upper. Possibly there may really be formed at the bottom (if there is a bottom) a sheet of pyroxenite corresponding to the early stage of crystallization, when this mineral alone is formed. Perhaps somewhere in the upper part or at some other horizon a sheet of labradorite may arise. But that is not the process advocated by Bowen.

Let us follow him. The crystallization begins with diopside, and later but while diopside is still forming, labradorite begins to crystallize. If before the crystallization of the feldspar two-thirds of the diopside and all of the magnetite have already crystallized, there will remain a leucocratic facies consisting of 80 per cent labradorite and 20 per cent diopside. But Bowen's scheme is somewhat different. When the feldspar begins to crystallize, it is not labradorite but the more basic bytownite, Ab_1An_1, that is formed. The specific gravity of this feldspar, according to Bowen himself, is very near to that of the liquid, so that these crystals would not sink in the original liquid. They do sink because the liquid after the crystallization of a certain amount of diopside, becomes of the composition of a syenite, and gets lighter. Indeed, if after the crystallization of two-thirds of the diopside, bytownite, Ab_1An_1, is formed, presumably in such quantity that one-half of the anorthite contained in the primordial magma has been spent, there will remain a mixture of nearly 50 per cent albite, 26 per cent anorthite, and 24 per cent diopside, or a syenite of the following composition:

	Per cent
SiO_2	62
Al_2O_3	19.5
MgO	2.6
CaO	7.2
Na_2O	8.5
	99.8

In this way, as we see, a soda syenite is formed, and in the later stages of Bowen's scheme a soda granite may arise. It must be noted that the syenites which are associated with anorthosites are not soda syenites but ordinary potash syenites.[1] Bytownite must

[1] The "mangerites" of Kolderup, which accompany the Norwegian labradorites and stand near to the nordmarkites, contain nearly equal quantities of soda and potash (5.51 per cent Na_2O and 6.57 per cent K_2O).

sink in this syenitic liquid. But we must not forget that this bytownite is, according to Bowen, only a temporary component. In the following stages of crystallization by reaction with the liquid, the albite is extracted, and gradually the feldspar is transformed into labradorite, representing the final product of crystallization. If so, the liquid will again change from syenitic to leucocratic-gabbroid, and the sunken crystals will once more float.

The foregoing considerations therefore, lead to two possibilities: (1) In consequence of the sinking and subsequent floating of the crystals while the diopside continues to crystallize, and in consequence of vertical and other currents that must arise under these circumstances, the crystals of diopside and labradorite will be mixed and no anorthosite will be formed. (2) If the crystallization proceeds in the manner assumed in the first case, namely if diopside and labradorite crystallize directly, there will be a tendency toward sinking and floating of the minerals. This tendency can produce a complete separation of the two minerals only in the case of mingling movements (as is illustrated in the separation of minerals in heavy liquids). Such movements being absent and the liquid being quiet, there can arise melanocratic and leucocratic facies with intermediate members, but of course not a syenite nor a granite.

Summary.—Summarizing all that has been said above, we must concede that the problem of the anorthosites and other monomineral igneous rocks is not yet completely solved. It must be conceded that in certain cases several factors, to which different authors refer, may possibly or actually take part in the formation of these rocks; but every attempt to put forward only one of these factors to the exclusion of the others, gives proof of exclusiveness and insufficiency. Indeed, such rocks as gabbros with anorthositic or pyroxenitic bands cannot be understood without admitting the existence of anorthosite and pyroxenite in the liquid state. But I am far from asserting that the only possible explanation is the hypothesis of liquid immiscibility, and that this is applicable to all forms of anorthositic rocks. And again, the possibility of the separation of crystals of pyroxene and labradorite from a gabbroic magma is sufficiently illustrated by the analogous phenomenon in porphyritic lavas, and is corroborated by their respective specific

gravities. But if we deduce from this that the gravitational distribution of crystals and crystallization-differentiation solves the whole problem of the anorthosites, we will meet with difficulties in the course of the crystallization, and especially in the fact that monomineral rocks represent relatively rare facies, while normal undifferentiated gabbro-noritic rocks are by far more frequent. Why, we must ask, does crystallization-differentiation not always lead to these final products of gravitative liquation? Bowen's experimental researches and his deductions from them, give inductions which in many points are theoretically correct for a theory of the crystallization of a gabbroic magma. But we have seen above that Bowen's scheme, based on the gravitational accumulation of crystals and operating with temporary minerals which disappear in the later stages of the crystallization of the magma, meets with several difficulties of theoretical and calculative character. I think, therefore, it is more correct to acknowledge that the problem of the monomineral igneous rocks and in particular, of the anorthosites, is not yet solved. It were better for this problem to remain an unsolved riddle to stimulate further investigations than to become, if unilaterally solved, a possible source of dogmatism.

PETROGRAD
May, 1921

THE GROWTH OF STALAGMITES AND STALACTITES[1]

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INTRODUCTION

The methods now in use for evaluating recent geological and remote archeological periods, in terms of years, are not numerous; therefore the addition of another method, even though it is only

[1] This paper received the Morrison prize of the New York Academy of Science.

an approximation, may be useful. A number of investigators during the last century have considered the question of the rate of stalagmitic growth as an aid in archeological chronology, but careful observations on different stalagmites gave such widely varying results that the observers were discouraged. This is not surprising since they expected to secure uniformity in results from stalagmites grown under very diverse conditions.

HISTORICAL

In 1874, W. Boyd Dawkins examined certain lime deposits in Ingleborough Cave, Devonshire, and came to the conclusion, "It may fairly be concluded, that the thickness of layers of stalagmite cannot be used as an argument in support of the remote age of the strata below."[1]

He repeated this opinion later.[2] In 1896, Horace C. Hovey, in writing of the stalagmites in Mammoth Cave, says, "Hence any estimate as to their age in years is idle and fruitless. It is only certain that they are *very old*."[3] George Byron Gordon[4] lists and discusses the factors affecting lime deposition, and gave the opinion, "It is evident, therefore, that the presence of a few inches of stalagmite is of little value in determining lapse of time." Charles Peabody and W. K. Moorehead,[5] in 1904, said, "Unfortunately absolutely nothing can here be adduced with precision," in referring to stalagmitic growth. Martel,[6] in 1900, said of stalagmites, "that their height cannot be considered in any way a contributing element to chronological calculations." Oliver Cummings Farrington,[7] in 1901, foresaw the possibility of estimating the age of some stalagmites.

[1] W. Boyd Dawkins (1874), pp. 38–41.

[2] W. Boyd Dawkins, *Quarterly Journal of the Geological Society*, LX (1904), 374.

[3] Horace C. Hovey, *Celebrated American Caverns* (1896), pp. 94, 95.

[4] "Caverns of Copan" (1896–1902), Peabody Museum, Harvard University, *Memoirs*, I, 11, 12, of the article on pp. 147, 148, of the volume.

[5] "Exploration of Jacob's Cavern," *Bull. No. 1, Dept. of Archaeology, Phillips Academy*, Andover, Massachusetts.

[6] *La Spéléologie ou Science des Cavernes*, Paris (1900), pp. 102, 103.

[7] "Observations on Indiana Caves," *Field Columbian Museum, Pub. 53, Geol. Series*, I (1901), No. 8.

FACTORS AFFECTING STALACTITIC DEPOSITION AFTER THE LIME SOLUTION HAS REACHED THE CAVE

1. Drip. Size of feeders.[1]

2. Rate of evaporation within the cave.[2] Air circulation, temperature, and humidity.

3. Diverting bodies under the drip.[3] Important only if relatively large in comparison with lime deposition.

4. Shifting of drip.[4] Complicates calculation of resultant mass. Not important.

5. Surface tension. Affects pendant drop.

6. Capillarity. One phase of surface tension which tends to hold solution in stalactitic tube.

7. Gravity.

The term "evaporation" includes the precipitation of the lime as basic carbonate by the removal of the carbonic acid from the solution, as well as the removal of the water.

A dripping stalactite means more solution than the evaporation conditions will handle. A small drip and rapid evaporation may mean no stalagmite and a rapid-growing stalactite. A rapid drip and poor evaporation may mean no stalactite but a slow-growing stalagmite[5] with large diameter. Small drip and poor evaporation gives slower growth and smaller diameter to the stalagmite.

STALACTITES

GROWTH OF STALACTITES

A stalactite forms as a slender tube,[6] which increases in diameter until the drip and evaporation reach equilibrium. The increase in diameter is effected partly by the creeping of the lime solution up over the rim of the stalactite and partly by the lime solution percolating from the inside of the tube outward through small

[1] Charles Peabody and W. K. Moorehead, *loc. cit.*

[2] George Byron Gordon, *loc. cit.*

[3] Charles Peabody and W. K. Moorehead, *loc. cit.*

[4] *Ibid.*

[5] *Ibid.*, p. 257.

[6] Chamberlain and Salisbury, *Geology*, Vol. I, *Processes* (2d ed. revised, 1909), p. 229.

channels in the stalactite wall. After drip-evaporation equilibrium is attained, the stalactite continues to grow *symmetrically*, (with uniform diameter) in the vertical direction, *unless conditions change.*

The removal of the carbonic acid from the pendant drop of lime solution causes the precipitation of the basic carbonate of lime as a thin, translucent film on the surface of the drop. If evaporation is good, this film is repeatedly broken and the pieces go spinning up to the rim of the tube—the drop is "alive." This spinning motion is due to surface tension and also to the fact that the down-flowing current is at the center of the drop and the up-flowing current at the periphery. Figure 3 shows a drop that is "alive"—good evaporation. Figure 5 shows a drop that is "dead"—poor evaporation.

Preceding the breaking away of the drop, there is a periodic, vertical oscillation which increases in frequency and amplitude until the actual break occurs.

EXAMPLES OF GROWING STALACTITES

Stalactites are growing under known evaporation conditions at the Experimental Mine of the United States Bureau of Mines, near Bruceton, Pennsylvania, on the concreted roof. Experimental coal-dust explosions are conducted in the mine during fall and winter, when the mine is dry, and high air is used to purge the mine of smoke and dust. The parts of the stalactites which grow during this period are blackened. This allows the rate of growth and the age of the stalactites to be closely determined. Also, certain of the stalactites are growing in the aircourse which is subject to violent explosions when the coal-dust work is under way. They are therefore no older than January 8, 1921, when the last explosion experiment was made. Unsymmetrical stalactite No. 2 grew in a gallery which was not completed until September 9, 1921. All these are rapid-growing stalactites of shell-like tube form, 0.4 to 0.5 cm. in outside diameter for the small part and about 1.0 to 1.2 cm. for the large part. The walls are about 0.02 cm. thick and are studded on the inside with small excrescences about 0.05 to 0.08 cm. thick. The rates of growth of the stalactites are given in Table I.

FIG. 1

FIG. 2

FIG. 3

FIG. 4

FIG. 5

FIGS. 1-5: Fig. 1.—Unsymmetrical stalactite No. 1; Fig. 2.—Unsymmetrical stalactite No. 1, enlarged about 6 diameters; Fig. 3.—Symmetrical stalactite No. 1; Fig. 4.—Unsymmetrical stalactite No. 2; Fig. 5.—Unsymmetrical stalactite No. 2, enlarged about 6 diameters.

TABLE I

RATE OF GROWTH OF EXPERIMENTAL MINE STALACTITES

Stalactite	Rate of Growth	Rate of Drip
	cm. per month	
Symmetrical No. 1	0.76	One drop every 21.8 minutes
Symmetrical No. 2	0.74	One drop every 81.0 minutes
Symmetrical No. 3	0.10	One drop every 5 seconds
Symmetrical No. 4	0.40	One drop every 3 seconds
Symmetrical No. 5	0.73	One drop every 46.2 minutes
Unsymmetrical No. 1	0.76	One drop every 53.3 minutes
Unsymmetrical No. 2	1.44	One drop every 13.8 minutes
Unsymmetrical No. 3	0.73	One drop every 18.8 minutes
Unsymmetrical No. 4	0.80	One drop every 6.1 minutes

EFFECT OF THE VARIOUS FACTORS AFFECTING THEIR GROWTH

These stalactites are shown as follows: unsymmetrical stalactite No. 1, Figure 1, enlarged about 6 diameters, Figure 2; symmetrical stalactite No. 1, Figure 3; unsymmetrical stalactite No. 2, Figure 4, enlarged about 6 diameters, Figure 5; unsymmetrical stalactite

FIG. 6.—Unsymmetrical stalactite No. 3

No. 3, Figure 6; unsymmetrical stalactite No. 4 and symmetrical stalactite Nos. 2, 3, 4, and 5, Figures 7 and 8, unsymmetrical stalactite No. 2 grew on green concrete, all the others on concrete from three to eleven years old. Carbonic-acid charged water evidently abstracts lime more easily from young concrete. Con-

centration then increases vertical growth. The only ones with rapid drips are symmetrical stalactites Nos. 3 and 4, which show that a rapid drip means a show vertical growth. The concentration of

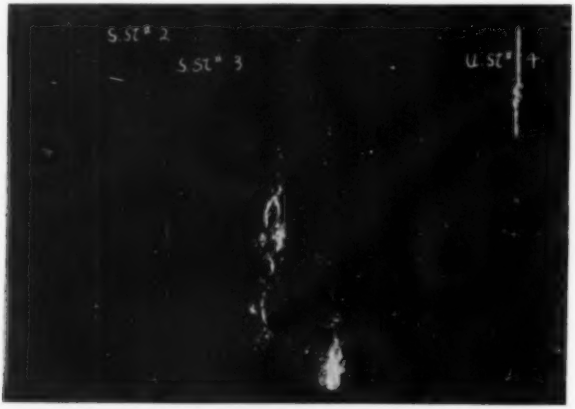

FIG. 7.—Symmetrical stalactites Nos. 2 and 3 and unsymmetrical stalactite No. 4

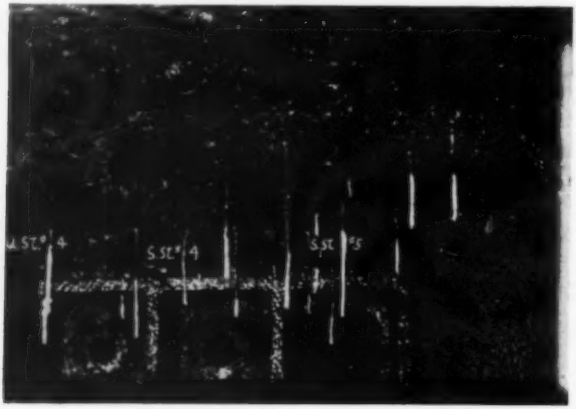

FIG. 8.—Unsymmetrical stalactite No. 4 and symmetrical stalactites Nos. 4 and 5

symmetrical stalactite No. 4 is greater than that of symmetrical stalactite No. 3.

The diameters of all the symmetrical and the small diameters of the unsymmetrical stalactites are about equal. Evaporation

conditions are also about equal. A certain concentration evidently is in equilibrium with the evaporation. When evaporation conditions are lowered, the lime solution has a greater time interval before precipitation after contact with the air. This allows the solution, providing the drip is not too rapid, to be spread out by capillary attraction before all the lime is precipitated. If the concentration is sufficiently high so that part of the lime remains unprecipitated after the solution is spread out, this residual lime is then precipitated over the enlarged diameter. The larger diameter means the effect of lowered evaporation upon a drip of fairly high concentration.

Rapid vertical growth is favored by high air circulation, high temperature, and high concentration, and is opposed by rapid drip and high humidity.

Large diameter is favored by low air circulation, low temperature, high concentration, and high humidity, and opposed by a rapid drip (Fig. 14).

Surface tension and capillarity greatly affect stalactitic growth, but stalagmitic growth hardly at all on account of the larger surface (necessary to evaporate the water received, which cannot drip away as in the case of a stalactite) with the consequent decrease of surface energy per sq. cm. Also, in the case of stalagmites, gravity works against surface tension and is therefore minimized.

The more variables that can be eliminated, the greater the chance for the solution of such a complex problem. The work on the rate of growth will hereafter be confined to stalagmites which are affected by rate of drip, air circulation, relative humidity, temperature, and concentration.

STALAGMITES

TABLE II

EXPERIMENTAL MINE STALAGMITES STUDIED

Stalagmite	Corresponding Stalactite	Drip	Circumference	Rate of Vertical Growth
		Sec.	m	cm. per year
No. 2	S.St. No. 3	3	.22	.70
No. 3	U.St. No. 4	368	.11	.60
No. 4	S.St. No. 4	5	.22	.60

These three stalagmites, among others, are shown in Figures 9 and 10, and in three-quarters view in Figure 11. Vertical and

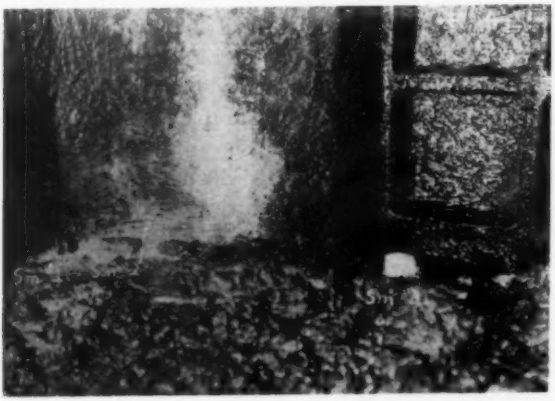

FIG. 9.—Stalagmites Nos. 1, 2, and 3

FIG. 10.—Stalagmites Nos. 3, 4, and 5

cross-sections of the three stalagmites studied are shown in Figures 12 and 13. The rate of growth is obtained from the "coal-dust bands" appearing in the vertical section. The light part of stalagmite No. 3 is colored red with iron, as is its corresponding stalactite.

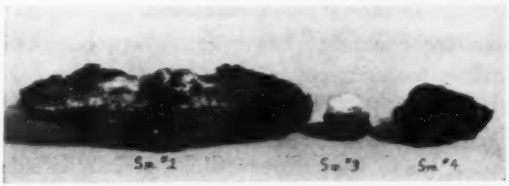

FIG. 11.—Stalagmites Nos. 2, 3, and 4, in three-quarters view

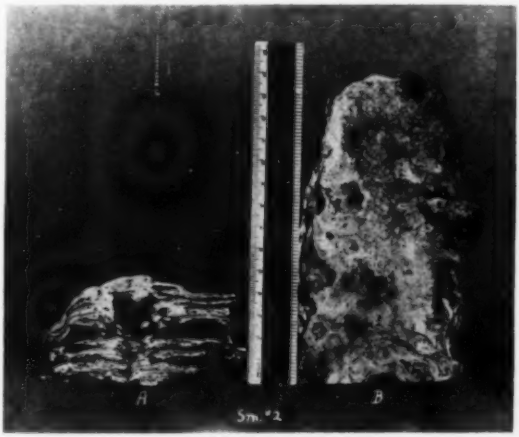

FIG. 12.—Stalagmite No. 2, vertical section and cross-section

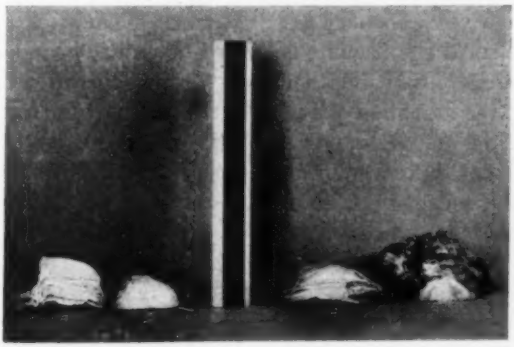

FIG. 13.—Stalagmites Nos. 3 and 4, vertical section and cross-section

EFFECT OF THE VARIOUS FACTORS UPON THE GROWTH

Approximately equal rates of vertical growth are noted for drips varying from 3 to 368 seconds, although the diameter increases with the rate of drip. The variation in concentration is very largely taken care of by the stalactite, especially in slower drips, before the solution reaches the stalagmite.

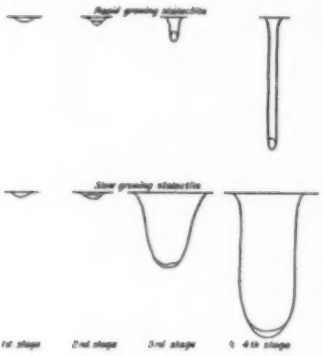

FIG. 14.—Diagrammatic outline of method of growth of stalactites.

"SPLASH CUP"

The cup at the top of some stalagmites is a "splash cup." Stalagmites Nos. 1, 2, 3, and 5 have cups of practically the same diameter, although of varying drip, and are about 40 cm. below their stalactites. The greater the distance of fall, the greater the diameter of the "splash cup." Symmetrical No. 4 has no cup on account of its greater concentration of drip. The cup of symmetrical No. 2 is deep, while the other cups are shallow; also its rate of drip is more rapid. The depth of the "splash cup" is increased by high evaporation, low concentration, and rapid drip.

THE MODE OF ORIGIN

At the start, a stalagmite is limited to a circle bounded by the splash of the drops hitting the floor. Good evaporation and rapid drip cause the formation of a saucer at the limit of the circle. The bottom of the saucer slowly rises as lime is deposited in it, and the excess solution cascades down over the rim and down the sloping sides of the stalagmite until such a diameter and convex surface are realized that the resulting evaporation surface will be just sufficient to evaporate the solution it receives. The stalagmite will now continue to grow vertically in a *symmetrical form unless conditions change.*

Poor evaporation and high concentration (or both) mean that the spattering drops will eventually form a small mound which will increase in height and decrease in diameter until the drip and evaporation surface is in equilibrium. It will then grow *symmetrically*, in a vertical direction, *unless conditions change* (Fig. 15).

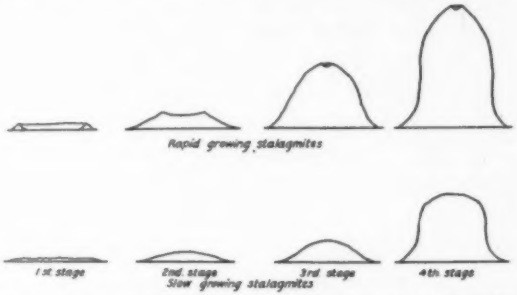

FIG. 15.—Diagrammatic sketch of method of growth of stalagmites

UNSYMMETRICAL STALAGMITES

A "mushroom" stalagmite is one in which the diameter has increased after a period of small diameter growth.

A "stool" stalagmite is a "mushroom" stalagmite in which the diameter has returned to about the same original diameter after the "mushroom" enlargement.

A "needle" stalagmite is one in which the diameter has decreased after a period of large diameter growth.

A "choked" stalagmite is one in which the diameter has returned to about the same original diameter after the "needle" effect had taken place.

The "mushroom" effect is caused either by an increase in the drip or a decrease in the conditions of evaporation. In the case of an increased drip, the slope between the original diameter and the enlarged diameter will be gentle because the vertical growth will increase slightly at the same time that the diameter increases. In the case of decreased conditions of evaporation, the slope between the original diameter and the enlarged diameter will be abrupt because the vertical growth will be decreased at the same time that the diameter is increased. If the original conditions return

again to about their previous magnitude, the stalagmite will exhibit a "stool" effect instead of a "mushroom" effect. A decrease in the drip or an increase in the evaporation conditions will cause the stalagmite to take on a "needle" form while if the conditions again return to about their original magnitude, the stalagmite will acquire a "choked" effect.

In the case of an abrupt slope between the large diameter and the small diameter (lowered conditions of evaporation), a lowered temperature is suspected because of its triple effect; decreasing the air circulation if the cave is ventilated by the thermal syphon method, reducing the vapor pressure of the lime solution, and increasing the absolute humidity. Evidence of a change in the air events of the cave will of course account for a change in the conditions of evaporation.

STALACTITIC CURTAINS

Observations on the stalactitic curtains behind symmetrical stalactites Nos. 2 and 3 Fig. 7 indicate that a slow drip, high concentration curtain will increase in thickness ("diameter") about one-fifth as rapidly as a stalagmite will grow vertically under corresponding conditions, and a rapid drip, low concentration curtain will increase in thickness about one-fortieth as fast as stalagmite will grow vertically.

SEASONAL INTERMITTENCY

Present seasonal intermittency can be ascertained by observation, and the *symmetry* of the stalagmite shows whether or not the present conditions held during its previous existence. If the stalagmite is "dead," the face will show a slight "needle" tendency, together with a corrugated or "petticoated" columnar section, similar to icicles,[1] if the drip has been seasonally intermittent.

GROWTH INDICATIONS

A sharply convex face means a rapidly growing stalagmite, and a blunt face means a slowly growing stalagmite. The deeper the "splash cup," the faster the drip, and the better the evaporation, and the wider the "splash cup," the greater the distance of fall. Absence of a "splash cup" means a high concentration.

[1] Farrington, *op. cit.*, p. 263.

CLASSIFICATION OF STALAGMITES

TABLE III

LIMITS OF FACTORS AFFECTING STALAGMITIC GROWTH

Factor	Upper Limit	Lower Limit	Ratio
Drip	*D* Five drops per second	*d* One drop per 5 minutes	1,500 to 1
Air circulation	*A* 500 cu. ft. per minute	*a* ½ cu. ft. per minute	1,000 to 1
Relative humidity	*H* 100 per cent	*h* 2 per cent	50 to 1
Temperature	*T* 90° F.	*t* 50° F.	40 to 1
Concentration	*C* 100 per cent	*c* 10 per cent	10 to 1

There are five factors given as affecting the growth of stalagmites, and each of these factors has been assigned two limits: an upper limit and a lower limit. Starting with the drip, it is seen that there will be two general classes of stalagmites: those with a large drip and those with a small drip. Each of these two classes will be further subdivided into two more classes: a class growing under high air circulation and a class growing under low air circulation. If these four classes are further subdivided according to high and low humidity, high and low temperature, and high and low concentration, it will be found that a total of thirty-two classes or types of stalagmites are possible.

It has been found that the circumference of a stalagmite is increased by fast drip and high humidity, and decreased by high air circulation and high temperature. This may be expressed by the relation: Circumference is proportional to

$$\left(\frac{D \times H}{A \times T}\right)^{\frac{1}{2}}$$

The $\frac{1}{2}$ power is used because it is in reality the surface or area of the face of the stalagmite that is affected, and this increases as the square of the diameter.

The rate of vertical growth of a stalagmite is favored by high air circulation, high temperature, high concentration, and to a small extent by a fast drip. The only factor opposing a rapid rate of vertical growth is high humidity. It can then be stated that the vertical growth is proportional to

$$\frac{A \times T \times C \times (12 + \log D)}{H}.$$

DIVISION INTO THIRTY-TWO TYPES

Each of the thirty-two types of stalagmites will have five factors affecting its growth. Some of these factors will have the upper limit and some of the factors will have the lower limit—it all depends upon the conditions surrounding the growth of the stalagmite. If these limits are substituted in the two foregoing formulas, a *relative* circumference and a *relative* rate of vertical growth can be calculated for each of the thirty-two types of stalagmites.

Also, by taking the two limits of the five factors as listed above, a "two-branching" or "dichoic" scale can be constructed, by means of which it is possible to tell the type that a given stalagmite belongs to, after first determining whether each of the five factors has the upper limit or the lower limit. This "dichoic" or "two-branching" scale now affords a way of finding out the type a stalagmite belongs to and, also, by means of the preceding method, to find out its *relative* circumference and its *relative* rate of vertical growth.

In Ingleborough Cave, Devonshire, England, there is a stalagmite called the "Jockey Cap," on account of its shape. This "Jockey Cap" stalagmite has been under observation since 1839, and its circumference growth and its rate of vertical growth are well known. By taking advantage of the measurements and comments of Dawkins[1] and Gordon,[2] the limits of the five factors governing the growth of the "Jockey Cap" can be ascertained, and accordingly the "Jockey Cap" can be classified by means of the "dichoic" scale as belonging to type 4. The mature circumference of the "Jockey Cap" may be estimated from the rate of circumference increase noted by Dawkins,[3] and using this mature circumference and the known rate of vertical growth of the "Jockey Cap," the *actual* circumference and the *actual* rate of vertical growth of type 4 becomes known. By the use of the *actual* circumference and *actual* rate of vertical growth of type 4 as a base, the *actual* circumference and *actual* rate of vertical growth for each of the thirty-two types can be obtained by means of the *relative* circumference and the *relative* rate of vertical growth previously calculated.

[1] *Op. cit.*, pp. 38–41, 442, and Appendix II.

[2] *Loc. cit.*

[3] *Op. cit.*, pp. 40, 442, and Appendix II.

The probable shape of the face, the presence or absence of a "splash cup," the circumference, and the rate of vertical growth, for each of the thirty-two types of stalagmites, have been assembled in Table IV. In addition, the Dichoic Scale has been tabulated. It is now possible, after determining the limits of each of the five factors, to classify the stalagmite, by means of the Dichoic Scale, as belonging to a certain type, and then, as a check, to compare four of the characteristics of this type of stalagmite in Table IV.

DICHOIC SCALE

1. The drip is large..... See 3 or 4
2. The drip is small..... See 25
3. The air circulation is large..... See 5 or 6
4. The air circulation is small..... See 15 or 16
5. The humidity is high..... See 7 or 8
6. The humidity is low..... See 11
7. The temperature is high..... See 9
8. The temperature is low..... See 10
9. The concentration is high, type 1; it is low, type 2
10. The concentration is high, type 3; it is low, type 4
11. The temperature is high..... See 13
12. The temperature is low..... See 14
13. The concentration is high, type 5; it is low, type 6
14. The concentration is high, type 7; it is low, type 8
15. The humidity is high..... See 17 or 18
16. The humidity is low..... See 21 or 22
17. The temperature is high..... See 19
18. The temperature is low..... See 20
19. The concentration is high, type 9; it is low, type 10
20. The concentration is high, type 11; it is low, type 12
21. The temperature is high..... See 23
22. The temperature is low..... See 24
23. The concentration is high, type 13; it is low, type 14
24. The concentration is high, type 15; it is low, type 16
25. The air circulation is large..... See 27 or 28
26. The air circulation is small..... See 37 or 38
27. The humidity is high..... See 29 or 30
28. The humidity is low..... See 33 or 34
29. The temperature is high..... See 31
30. The temperature is low..... See 32
31. The concentration is high, type 17; it is low, type 18
32. The concentration is high, type 19; it is low, type 20

33. The temperature is high ..... See 35
34. The temperature is low ..... See 36
35. The concentration is high, type 21; it is low, type 22
36. The concentration is high, type 23; it is low, type 24
37. The humidity is high ..... See 39 or 40
38. The humidity is low ..... See 43 or 44
39. The temperature is high ..... See 41
40. The temperature is low ..... See 42
41. The concentration is high, type 25; it is low, type 26
42. The concentration is high, type 27; it is low, type 28
43. The temperature is high ..... See 45
44. The temperature is low ..... See 46
45. The concentration is high, type 29; it is low, type 30
46. The concentration is high, type 31; it is low, type 32

TABLE IV

TABLE OF CHARACTERISTICS

Type	Cup	Shape of Face	Rate of Growth	Circumference	Limits of Variable
			cm. per year	m.	
1.....	Shallow	Very convex	3000	0.6943	*D, A, H, T, C*
2.....	Deep	Very convex	300	0.6943	*D, A, H, T, c*
3.....	Shallow	Very convex	7.5	4.4	*D, A, H, t, C*
4.....	Shallow	Very convex	0.75	4.4	*D, A, H, t, c*
5.....	Deep	Very convex	15000	0.0981	*D, A, h, T, C*
6.....	Very deep	Very convex	1500	0.0981	*D, A, h, T, c*
7.....	Shallow	Very convex	450	0.6213	*D, A, h, t, C*
8.....	Deep	Very convex	45	0.6213	*D, A, h, t, c*
9.....	Shallow	Convex	0.2985	21.9120	*D, a, H, T, C*
10.....	Shallow	Convex	0.0299	21.9120	*D, a, H, T, c*
11.....	Very shallow	Convex	0.0075	138.9080	*D, a, H, t, C*
12.....	Shallow	Very blunt	0.0008	138.9080	*D, a, H, t, c*
13.....	Shallow	Very convex	15	3.1051	*D, a, h, T, C*
14.....	Very deep	Very convex	1.5	3.1051	*D, a, h, T, c*
15.....	Shallow	Very convex	0.3750	19.6416	*D, a, h, t, C*
16.....	Very deep	Very convex	0.0375	19.6416	*D, a, h, t, c*
17.....	Very shallow	Very convex	237.2250	0.0180	*d, A, H, T, C*
18.....	Shallow	Very convex	23.7225	0.0180	*d, A, H, T, c*
19.....	None	Very convex	5.7370	0.1131	*d, A, H, t, C*
20.....	Shallow	Convex	0.5737	0.1131	*d, A, H, t, c*
21.....	Very shallow	Very convex	11850	0.0026	*d, A, h, T, C*
22.....	Very deep	Very convex	1185	0.0026	*d, A, h, T, c*
23.....	Very shallow	Very convex	2933	0.0158	*d, A, h, t, C*
24.....	Very deep	Very convex	293.3	0.0158	*d, A, h, t, c*
25.....	None	Convex	0.2373	0.5667	*d, a, H, T, C*
26.....	Shallow	Blunt	0.0237	0.5667	*d, a, H, T, c*
27.....	None	Convex	0.0059	3.5816	*d, a, H, t, C*
28.....	Deep	Blunt	0.0006	3.5816	*d, a, H, t, c*
29.....	Very shallow	Very convex	11.8500	0.0805	*d, a, h, T, C*
30.....	Very deep	Convex	1.1850	0.0805	*d, a, h, T, c*
31.....	Shallow	Blunt	0.0293	0.5068	*d, a, h, t, C*
32.....	Shallow	Blunt	0.0029	0.5068	*d, a, h, t, c*

ACTUAL CLASSIFICATION OF STALAGMITES

If a stalagmite is extremely *unsymmetrical*, it may be necessary to classify it by sections. The classification, by circumference alone (a more or less uncertain procedure), will indicate its period of formation, but not how long ago it died. If a stalagmite is young (immature) and its drip large, its circumference will be less than that given in Table IV; if the stalagmite is young and its drip small, its circumference will be greater than that given in the Table IV.

More than one drop per second is a fast drip, over 2 feet per second (perceptible) is a large air circulation, over 50 per cent is a high relative humidity, over 68° F. is a high temperature, and over 50 per cent is a high concentration.

Count the drip, estimate the air, get the concentration by analysis (the absence of a healthy stalactite above indicates a high concentration if the cave has a pure limestone cover), and determine the temperature and humidity. If the stalagmite is in an open cavern or shelter, the yearly average temperature and relative humidity for the region may be taken.[1] A wet cave, of course, means a high humidity.

PRECAUTIONS NECESSARY

After determining your limits, classify by the Dichoic Scale and verify the measurements in Table IV. Always remember that the classification involves the extreme limits of the variables, and if unsatisfactory results are obtained re-examine the limits and, if any are doubtful, reclassify. Table IV is merely an approximation, and the figures are given to several decimal places to prevent a ragged appearance.

EXAMPLES OF CLASSIFICATION RESULTS

The actual figures are based on the Jockey Cap. Figure 16 shows an attempt to reconstruct this stalagmite from Dawkin's[2] measurements. On the basis of the foregoing calculations, this stalagmite now (1922) has a circumference of 3.53 meters, or 139 inches, at the points located by Dawkins.

[1] "Climatological Data by Sections," *U.S. Weather Bureau.*

[2] *Op. cit.*, pp. 40, 442, and Appendix II.

"The Pillar of the Constitution," Wyandotte Cave, Indiana,[1] classified by circumference alone (a precarious method), falls into type 10 as being the slowest-growing stalagmite consistent with its circumference. The age of this stalagmite has been estimated as follows:[2]

Authority	Rate of Growth	Period of Formation
	cm. per year	years
Collet	0.010	91,000
Collet	0.017	54,000
Collet	0.025	37,000
Hovey	0.025	37,000
Present estimate	0.030	30,500

The stalagmite in the Museum of Science and Art, Edinburgh[3] (classified again by circumference alone), required 560,000 years for its formation. Sir Alexander Milne measured the increase on the stump which accrued from 1819 to 1863 and estimated the age at 600,000 years.

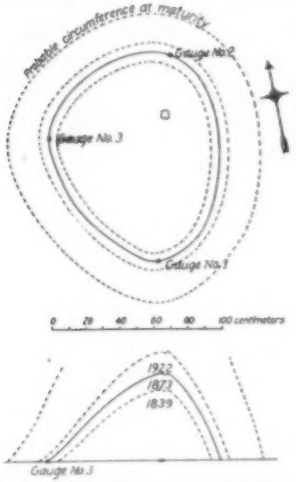

FIG. 16.—Jockey Cap stalagmite, Ingleborough Cave, drawn from Dawkin's measurements, 1873.

The Experimental Mine stalagmites fall in type 20, and agree fairly well in vertical growth (0.57 cm. against about 0.60 actual) and circumference. These stalagmites are undoubtedly calcite (W. M. Myers, petrographer, Pittsburgh Station, United States Bureau of Mines, reports that fragments of the stalagmites were uniaxial negative, refractive index from 1.486 to 1.658, and gave Meighen's reaction for calcite).

The change in shape, convexity of face, and circumference of the stalagmite from Robertson's Cave, near Springfield, Missouri,[4] were probably caused by a sudden increase in drip and an increase

[1] Farrington, *loc. cit.* [2] *Ibid.* [3] *Ibid.*, p. 255.

[4] Farrington, *op. cit.*, p. 1; vertical section, Plate 32.

in evaporation, accompanied by a slight movement of the drip.[1] This caused a more rapidly growing stalagmite of a little greater diameter.

Several stalactites and stalagmites are now under observation in Marengo Cave, Indiana,[2] but their growth is probably slow.

CONCLUSIONS

An approximation method for determining the age of stalagmites has been developed.

Symmetry in a stalagmite indicates constant growth conditions.

Stalagmites with circumferences of over 25 meters generally occur as stalagmitic or travertine layers, as they rarely have sufficient space to permit them to attain their mature circumference.

ACKNOWLEDGMENTS

I wish to thank Dr. Herbert Insley, formerly petrographer for the Pittsburgh Station of the United States Bureau of Mines, and now with the United States Bureau of Standards, at Washington, D.C., for his assistance and suggestions; also Dr. Clark Wissler, curator of anthropology, American Museum of Natural History, New York City, for his assistance in securing access to rather uncommon publications.

[1] *Ibid.*, p. 258.

[2] Farrington, *loc. cit.*

THE PHYSIOGRAPHIC DEVELOPMENT OF THE BIG THOMPSON RIVER VALLEY IN COLORADO[1]

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OUTLINE

INTRODUCTION
DESCRIPTION AND CLASSIFICATION OF UNITS
PRE-WISCONSIN GLACIATION
HISTORY OF THE UNITS IN THE BIG THOMPSON VALLEY
SUMMARY

INTRODUCTION

The Big Thompson River rises in a snow field within a large cirque on the east side of the Continental Divide in Colorado at about latitude 40° 20′ north. It flows in a general easterly direction down the slope of the Front Range to cross the foothills and the plains, joining the South Platte River east of Greeley. The portion of the Big Thompson River under consideration may be found on the Longs Peak, Mount Olympus, and Loveland quadrangles. The contour interval (100 feet) is too large, however, to permit map identification of many features included in this report. The accompanying sketch map (Fig. 6) gives the location of the various places discussed.

The composite origin of the Big Thompson Valley may be clearly shown from a study of the five distinct and successive physiographic units which make up its course from headwaters to foothills district. The separation of the different parts of the valley into five areas is based upon: (1) general outline and contour of the valley walls; (2) number and character of the tributary streams.

[1] Observations on the physiography of Big Thompson River Valley occupied parts of the field seasons of 1921 and 1922 while the author was engaged in a study of the Pre-Cambrian geology of the Front Range in northern Colorado.

DESCRIPTION AND CLASSIFICATION OF PHYSIOGRAPHIC UNITS

1. The first unit extends for about 12 miles from the Continental Divide east through Moraine Park (Fig. 6). Beginning at the Continental Divide the first unit is typical of the topography developed by late Pleistocene glaciation. At present the tributary in Spruce Canyon harbors the Sprague Glacier—a remnant of the larger masses of ice which grooved and scoured the granite and schist of stream-carved canyons into U-shaped valleys with many hanging tributaries. The chief tributary once occupied by the late Wisconsin ice is the Fall River, the lower part of whose valley was the melting basin (Horse Shoe Park) of an ice tongue similar to that which filled the Big Thompson in Moraine Park and developed huge lateral moraines.

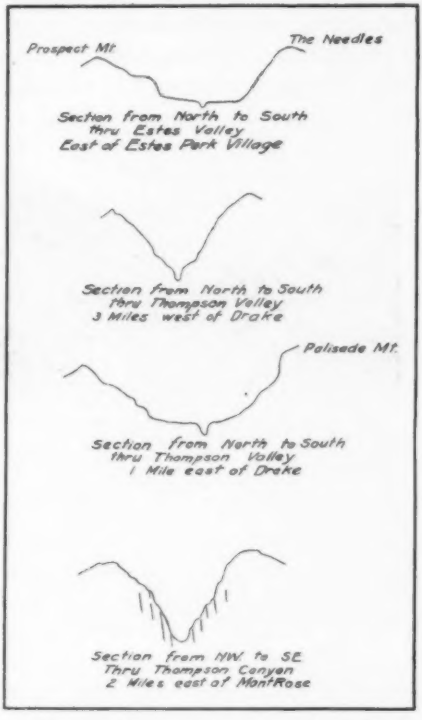
Prospect Mt.
The Needles
Section from North to South thru Estes Valley East of Estes Park Village
Section from North to South thru Thompson Valley 3 Miles west of Drake
Palisade Mt.
Section from North to South thru Thompson Valley 1 Mile east of Drake
Section from NW. to SE. Thru Thompson Canyon 2 Miles east of MontRose

FIG. 1.—Diagrammatic cross-sections of the valleys of units 2, 3, 4, and 5 of the Big Thompson River Valley.

2. The second unit comprises the Estes Valley. This area has a broad, flat T-shaped outline. From Moraine Park to Estes Village the valley is from 1 to 2 miles wide. East of the Village it widens and lengthens north to Devils Gulch and south to include Fish Creek Valley. On all sides of this broad, flat surface granite walls rise abruptly so that for a distance of nearly 7 miles the valley is marked at its margin by precipitous granite cliffs, i.e., the Needles in Estes Park (Fig. 1).

Black Canyon on the north, Fish Creek Valley on the south, and Dunraven Valley on the east between Mounts Olympus and Pisgah are tributary to the Thompson within this area. They, like their main, are broad, open, and U-shaped. The Thompson has sunk its channel from 50 to 100 feet below the broad level of the Estes Valley and locally has developed intrenched meanders.

3. The third unit begins at the eastern end of the Estes Valley. The sides are sharply constricted within granite walls, making a V-shaped canyon with precipitous slopes increasing in steepness to the east of Loveland Heights and Glen Comfort. From Estes Valley to the Forks at Drake the river's course lies through a canyon whose tributaries are narrow gulches typical of youthful stream erosion.

FIG. 2.—View looking upstream through Mont Rose Valley (unit 4). Note the open U-shaped outlines of the valley walls with the sharp unglaciated peaks of Palisade Mountain in the distance.

4. The fourth unit lies between Drake and the east end of Mont Rose Valley (Fig. 2). In this area the Big Thompson Valley is wider than above Drake, although not as wide as in Estes, and has a broad, U-shaped outline. The stream has sunk its channel over 100 feet into the bottom of this open valley and has made a narrow canyon about 6 miles long which marks the last cycle of canyon cutting.

The North Fork enters the Thompson at Drake. This stream valley is open and U-shaped in outline with gently rounded *roche moutonné* surfaces developed on the granite in the upper part of the valley bottom. As seen from Bryant's Ranch the valleys of the North Fork and the Big Thompson are much alike. In fact they are so similar that one seems but a continuation of the other. The North Fork and the part of the Big Thompson between Drake and Mont Rose are in perfect harmony, while the upper part of the Big Thompson between Estes and Drake is entirely out of accordance with the lower reaches.

Cedar Creek, which enters the Thompson Valley about a mile west of Mont Rose, is also open and U-shaped, with steepened sides in accordance with the main valley. Small tributaries of the Thompson within the fourth unit are narrow gulches developed by recent stream erosion. All the gulches from Estes Valley to Mont Rose, however, were begun before the last cycle of canyon-cutting. When traced from their junction with the Thompson to their headwaters they show a narrow steep-walled canyon in the lower reaches opening out into wider middle and upper portions.

5. The fifth unit is the Loveland Canyon (Fig. 3). From Mont Rose to the foothills the valley is a deep box canyon whose sides rise from 100 to 1,000 feet above the stream. The lower walls are nearly vertical and are the dipping surfaces of almost perpendicular beds of highly indurated schist. For the most part the river's course lies along the strike of the schistosity and crosses the dip only at right angles with sharp and short turns.

FIG. 3.—Same location as Figure 2 but looking downstream into the gorge of unit 5.

The second and fourth units have the following features in common: (1) open flat-bottomed valleys with steep walls; (2) intrenched meanders in the bottom of the broad valleys. The third and fifth units also have many similar features as: (1) narrow, V-shaped outlines; (2) precipitous tributary gulches (Fig. 1). It will be shown that the second and fourth physiographic units have had a similar development, but entirely different in its aspects from the processes which developed units 3 and 5.

The course of the Big Thompson River lies almost at right angles to the strike of the Front Range and reveals a section of the Pre-Cambrian beds from the Continental Divide to the foothills.

The river's course is a series of sharply twisted meanders. Where straight stretches do occur they lie along dipping beds of schist and the more abrupt turns follow the prevailing joint systems in the granite and schist. The river first crosses granite with small amounts of schist, then crosses an area chiefly of granite from Estes Valley to Loveland Heights. To the east the granite is more and more interrupted by schist until at Drake, schist and massive pegmatite dikes predominate. East of Drake, through the fourth and fifth units, the course is parallel to the dip of the steeply dipping beds of schist for most of the distance. Both units, although so different in appearance, are developed in much the same sort of rock. The schist, except locally, is the least resistant, the pegmatite next, and the granite the most resistant of the rocks exposed along the river's course. Hence canyons in schist at the lower end of the valley and broad, open stretches in granite near the upper part must owe their sequence to factors other than simple stream erosion.

PRE-WISCONSIN GLACIATION

It is believed that there are, within the area drained by the Big Thompson, evidences of a much earlier Pleistocene glaciation than the late Wisconsin invasion. There are four principal lines of evidence of this earlier glaciation.

1. *U-shaped valleys.*—The U-shaped outlines of portions of the main valley have already been pointed out in the description of the second and fourth units. Mountain valleys which have been occupied by glaciers always show a characteristically U-shaped profile, rounded and scoured by the ice to its upper limits on the valley walls, with the surrounding unglaciated peaks left steep and serrate. The profile of Mont Rose Valley (Figs. 1 and 2) shows a typical U-shape, with Palisade Mountain exhibiting steep and sharp peaks above the rounded outline. The Estes Valley is also distinctly U-shaped, but the ice evidently rose to overlap its margin north and south of Estes Village. To the east, however, the profile of Mounts Olympus and Pisgah exhibit sharp peaks which stood well above the ice in the valleys below.

In addition to these regions already described there are flat areas of oval shape such as the Orchard and Cedar Park (Fig. 4).

They have the appearance of having been the melting basins of ice which gathered from the surrounding highlands. The appearance of peaty beds in the soil of Cedar Park adds to this evidence although no true till has yet been recognized from the area.

2. *Remnants of early till.*—There are remnants of early till exposed along the roadside at the east end of Mont Rose Valley. This till is made up of granite bowlders, with rounded and scored surfaces, buried in a matrix of bluish clay. The whole is overlain by stratified beds of sand and clay topped by coarse gravels.

FIG. 4.—Cedar Park—probably the melting basin of glaciers which centered around Storm Peak in the distance.

Small patches of glacial bowlders and terrace gravels lie about 50 feet above the river on a rock terrace at Cedar Cove. They are probably remnants of more extensive glacial deposits belonging to the earlier ice invasion. River erosion since ice occupation has re-worked these deposits—carried off most of the lighter sands and rock flour, leaving only the larger bowlders perched above the present course of the river, which has intrenched itself in recent times from 50 to 100 feet below the old glaciated floor. Recent talus and slumpings may have covered most of the drift remnants which might be expected to remain along the sides of the valley east of Drake. In the Estes Valley, no true till remnants remain, but terrace gravels of water-worn glaciated pebbles perch about 100

feet above the stream level at the base of steep granite walls on the north side of the valley.

3. *Potholes.*—Nearly every exposure of granite in the Estes Valley is marked by several well-defined potholes which vary in size from some 3 or 4 inches in diameter and 1 or 2 inches deep to others 2 feet deep and 4 feet across (Fig. 5).

Most of them are nearly circular with the margin broken down on one side. The margins of these potholes have been etched by weathering so that large angular feldspar crystals protrude into

FIG. 5.—Glacial potholes cut in granite along the Estes Valley

the cavity like small teeth. Within the holes the surface is smoother, and in some grooved so deeply that a secondary pothole has been cut within the original one.

These potholes are found at all elevations from the summit of Prospect Mountain, 8,896 feet, and the Needles, 10,075 feet, to the level of 7,500 feet on the floor of Estes Valley. They also appear in Fish Creek Valley up to the top of Lily Mountain, 9,793 feet. They are believed to mark the margin of early glaciers which filled the Estes Valley where whirlpools following the drainage retreated into the valley with the floods from the waning ice. From Drake to Mont Rose there are a few poorly preserved potholes in the schist. It appears that the schist and pegmatite are not massive enough to

preserve the form of those that might have existed and probably were too fissile to allow the production of potholes on the scale to which they appear to have been developed in the granite.

4. *Interrupted and reorganized drainage lines.*—The interrupted and reorganized drainage lines are directly the result of the ice occupation of units 2 and 4.

The diagrams in figures 6 and 7 suggest a possible analysis of the drainage before and after the early glaciation. The valley of

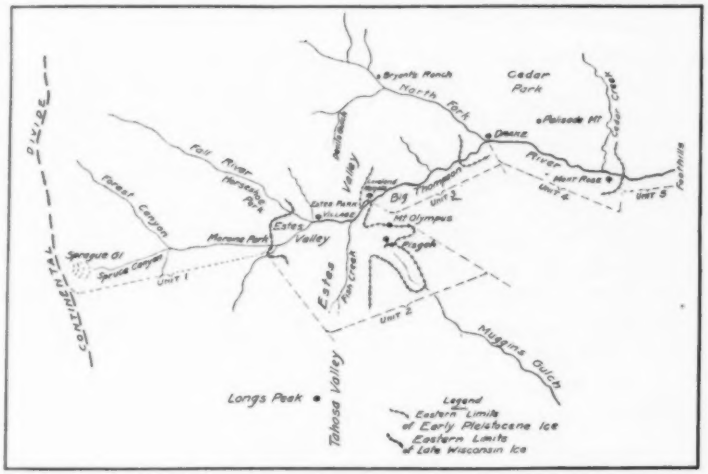

FIG. 6.—Diagram of the present drainage of the area showing influence of early and late glaciation on the present drainage lines.

Muggins Gulch is suggested as the outlet of the upper Thompson in preglacial times. The North Fork is shown as the headwaters to the lower part of the Thompson of today. Small tributaries to each occupied the present course of the Big Thompson between Estes Valley and Drake and were separated by a low col.

The early ice gathered on the highlands to the west and moved down the Estes Valley as far east as Mount Olympus, while small valley glaciers filled in Black Canyon and the valleys around Olympus and Pisgah. Probably Park Hill and Muggins Gulch were also full of ice, and possibly all of the Estes Valley south to include

Tahosa Valley. The Estes Valley was the melting basin of this whole system of glaciers, though the drift deposits left in the glaciated area have been cleared out by long and active erosion of the stream and ice tributaries, leaving a U-shaped valley as chief evidence of its occupancy. Simultaneously ice gathered in the valleys adjacent to Storm Peak and filled in the North Fork, Cedar Park, and the Thompson Valley between Drake and Mont Rose.

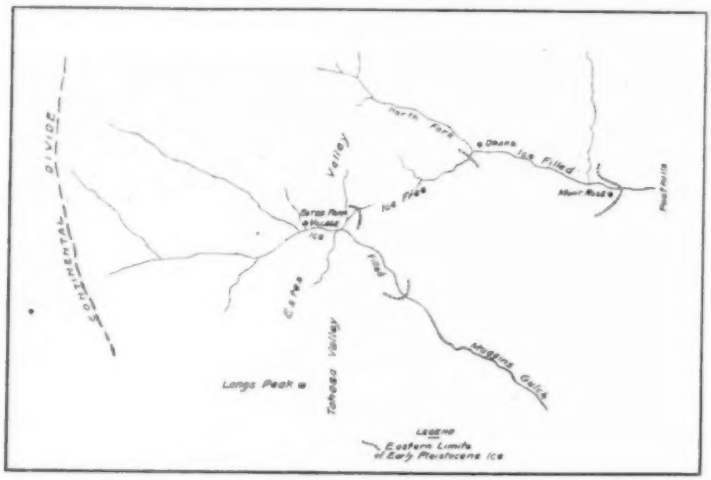

FIG. 7.—Diagram to represent the suggested drainage systems which preceded early Pleistocene glaciation of this area.

When the Muggins Gulch outlet was filled with ice to the 9,000-foot level, drainage traveled from Estes to Drake over the low col and through the small tributaries. This outlet became more important as an escape for all the waters from the upper Thompson after the ice had melted from the lower altitudes of the Thompson Valley east of Drake. On account of its lower elevation the ice freed the area east of Drake while it may have lingered for some time in the Estes Valley to the west. As a result, the drainage once established along its present lines east of Estes rapidly cut down its course below the 8,000-foot level, thus determining the upper canyon

of the Thompson. When the ice finally melted from the Estes basin to the west, drainage had been permanently established along its present lines throughout most of the Thompson Valley.

The combined features of U-shaped valleys, remnants of till, glacial potholes, and interrupted and reorganized drainage furnish ample proof that glaciers invaded, eroded, and melted from portions of the Thompson Valley in early Pleistocene times.

HISTORY OF THE UNITS IN THE BIG THOMPSON VALLEY

The five different units comprising the Thompson River Valley are believed to have been the result of several processes affecting two distinct river systems.

The essential elements of these processes in chronological order comprise: (1) normal stream erosion; (2) Early Pleistocene valley glaciers; (3) Early glacial drainage; (4) late Pleistocene valley glaciers.

Normal stream erosion first determined the courses of both river systems. Probably both streams developed steep-walled canyons along much of their courses. The areas occupied by units 1 and 2 of the present Thompson River Valley were the upper reaches of the western (Muggins Gulch) river system, while units 2 and 4 comprised the middle portions of the eastern (North Fork) river valley. Unit 3 is the connecting link between these areas and is the youngest topographic feature of the present Thompson Valley. Unit 5, which was the lower part of the eastern river valley, is probably the only unmodified portion of these early systems which were incorporated into the Thompson. As far as the present analysis goes, this gorge (unit 5) has been a simple stream-carved canyon throughout its history.

The stream cycle of erosion was interrupted by early Pleistocene valley glaciers which filled in the headwaters and middle reaches of both river systems modifying the outlines of the parts which later became units 1, 2, and 4 from V-shaped gorges to open U-shaped valleys. Drainage from the western ice-filled valley escaped both through Muggins Gulch and over the low col to the east through the eastern stream valley to the foothills. The later outlet became the site of *all* the drainage from the west when the

waters had cut the new eastern outlet below the level of Muggins Gulch after the ice had left the eastern (North Fork) valley.

Proofs of the exceedingly youthful character of unit 3 are derived from a study of the gradient of the present Thompson Valley.

The gradient of the Big Thompson River averages from Estes to the foothills about 100 feet per mile. About 3 miles west of Drake along unit 3 the gradient is nearly 250 feet per mile for a distance of over 2 miles. This is the steepest fall along the river's course which is here between nearly vertical canyon walls cut alike in granite and schist. As far as erosion by the stream alone is concerned this stretch is the youngest topographic feature along the entire course of the river. This portion of the valley is solely the result of stream erosion established by early glacial drainage across a low divide which developed into a steep and winding canyon widening east to Drake and west to Estes Valley.

The early Pleistocene glaciers left units 2 and 4 much as they are today except that recent stream erosion resulting from an upwarp of at least 100 feet over much of the area has cut a canyon 50 feet to 100 feet deep in the floors of units 2 and 4 and has cleaned out the early glacial débris from the botton of the valley.

In late Pleistocene (probably late Wisconsin) times ice again advanced over part of the course of the Big Thompson but to a much less extent than in early Pleistocene times. The limits of this invasion mark the boundaries of unit 1 where massive terminal moraines separate the areas which have been influenced by both early and late glaciation (unit 1) from that which was covered by the early ice only (unit 2).

During and perhaps previous to late Wisconsin glaciation the Big Thompson Valley stood about 100 feet lower than at present. At any rate, débris from the melting of the ice was deposited as a thick layer of sand and gravel over the flatter parts of the valley floor outside of the late Wisconsin ice area.

As the Wisconsin ice vanished an upwarp of at least 100 feet affected most of the area. The river promptly dissected most of the terrace deposits and began sinking its channel into the bedrock, producing a canyon within a canyon in units 3 and 5 and letting a narrow canyon nearly 100 feet deep into the broad floors of units 2

and 4. At the present time these inner canyons are being rapidly degraded, and at no points outside of unit 1 is there any aggradation taking place.

SUMMARY

The composite course of the Big Thompson River Valley comprises five units linked together as a result of the complex physiographic history of the area from the Continental Divide to the foothills district.

Lines of evidence point to two distinct river systems flowing independently but in the same general direction to the foothills. Canyon-cutting by these two streams was interrupted by early Pleistocene glaciers which filled in the headwaters and crept far down each valley toward the foothills. The glaciers blocked the normal drainage outlets of the western (Muggins Gulch) river system and its waters traveled east over a low divide to the eastern (North Fork) valley which, because of its lower altitude was freed from ice while glaciers still filled the western area. The drainage lines thus established from the western to the eastern river systems became the connecting link in the new river valley—the Big Thompson of today. Late Pleistocene glaciers affected only the headwaters of this new system and are in no way responsible for the general course of the Big Thompson.

Thus the present river valley is made up of the glaciated headwaters of one river system joined by a young precipitous stream-carved canyon to the glaciated middle portions of another river system and the whole extends east through a river-cut gorge across the foothills and the plains of eastern Colorado to join the North Platte River east of Greeley.

NOTES ON MUD CRACK AND RIPPLE MARK IN RECENT CALCAREOUS SEDIMENTS[1]

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During a trip to Florida and the Bahamas in the winter of 1920, the writer kept in view as one of the objects of his seashore studies the discovery of localities favorable for noting the characteristics of mud cracks in Recent sediments. It seemed desirable that the results obtained in laboratory experiments dealing with this subject should be checked by comparison with mud cracks formed on the seashore. The following notes include also some observations relating to ripple marks on calcareous sand.

MUD CRACKS

In the writer's experimental work, saline and non-saline mud cracks were shown to develop, under the experimental conditions imposed, sharply contrasted features. The polygons of the non-saline mud cracks turned upward while those of the saline mud cracks remained flat or curved slightly downward. It was stated in this paper[2] that while the experiments indicated the tendency of the polygon margins to curl upward in the one case and remain flat or curve downward in the other, the conditions found in nature may often disguise or prevent any effective exhibition of these contrasting tendencies. It was pointed out also that "the marked differences observed in the experiments between the behavior of fresh-water, highly saline, and moderately saline muds are not ordinarily so well marked in nature as the accompanying illustrations might lead the reader to expect."[3]

In the following notes the reader will see to what extent the conclusions reached from experimental work regarding the contrasts

[1] Published with the permission of the director of the Geological Survey of Canada.

[2] "Some Factors Affecting the Development of Mud Cracks," *Jour. Geol.*, Vol. XXV (1917), pp. 135–44.

[3] *Op. cit.*, p. 143.

between saline and non-saline mud cracks are supported by seashore observations made in Florida.

In southern Florida, the calcareous deposits commonly met with on or near the beach consist either of calcareous sand or flocculent calcareous ooze. The two kinds of deposits are apt to be sorted by wave and current action both on the beach and in the shallow waters near shore in much the same manner as ordinary mud and quartz sand, resulting in beaches of pure white or cream-colored sand separated by bays of soft gray ooze containing more or less intermixed calcareous sand. The calcareous sand suffers no appreciable loss of bulk on drying and consequently does not sun-crack. Since this material forms the bathing beaches which are familiar to tourists from the North, the casual visitor is apt to get the impression that mud cracks do not develop on the recently formed calcareous marine deposits. The soft, flocculent, calcareous mud, however, reacts to sun and atmospheric exposure in the same way as ordinary mud. The writer was able to see examples of mud cracks on the calcareous mud at only a few localities. One of these is the shore line on Key West Island between the bathing-beach and the United States Bureau of Fisheries laboratory. The flat limestone shore here lies but slightly above the high tide line. At a few points along this shore a thin veneer of calcareous mud occurs both within the intertidal zone and slightly above it, where it has been left during spring tides or periods of unusual inundations accompanying storms. Along this stretch of shore good examples of mud cracks were seen both in the salt-water zone and above it. In the latter, all the examples observed showed polygons with the margins turning up. In the salt-water mud cracks the margins curved downward often sufficiently to lift the center of the polygon clear of the ground.

Various other stretches of the shore line, both in south Florida and on Providence Island, Bahamas, were examined for mud cracks, but no very satisfactory localities were seen for extensive subaerial exposures on natural beaches of the type of calcareous sediment capable of developing mud cracks. Fortunately, however, the extensive dredging operations, which were undertaken for the purpose of reclaiming swamp land near Miami beach, gave the

writer an opportunity to see several acres of the calcareous mud which forms much of the bottom of the northern part of Biscayne Bay exposed to subaerial conditions. North of the causeway to Miami beach six or eight acres had been covered by gray calcareous mud pumped from the shallow sea bottom by hydraulic dredges. The resulting expanse of mud cracks furnished an exceptional opportunity for observing the kind of mud cracks which this type of sediment will yield (Fig. 1).

These mud cracks show a considerable range in the size of the polygons. Over most of the area the polygons were from 6 to 15

FIG. 1.—Mud cracks in calcareous mud, Miami, Florida. Note terrace-like margins of polygons.

inches in diameter, with cracks separating them which were mostly from $2\frac{1}{2}$ to 3 inches wide, but with a minimum and maximum range of from $\frac{3}{4}$ to 4 inches in width. The depth of the cracks generally ranged between 8 and 15 inches. One part of the area was noted where the polygons ranged between 1 and $3\frac{1}{2}$ feet in diameter with the separating cracks averaging 3 inches in width (Fig. 2). These large polygons showed none of the tendency to split up into laminae seen in some of the smaller ones (Fig. 3). The margins of the polygons of Figure 1 show clearly three or four laminae exposed,the unequal rates of shrinkage having developed terrace-like margins along the fissures. The different-sized polygons noted in different parts of the Miami mud cracks probably correspond to differences in the desiccating power of the sun when they were formed. A high

temperature tends to produce more widely spaced mud cracks than a lower one, according to the writer's experiments.[1]

With reference to curvature or flatness of the surfaces of the polygons, the behavior was nearly but not entirely uniform. With a very few exceptions, the polygons showed flat or very nearly flat

FIG. 2.—Mud cracks with flat-topped polygons 1′ to 3½′ in diameter; Miami, Florida

FIG. 3.—Calcareous mud cracks splitting into laminae; Miami, Florida

surfaces (Figs. 1–3). In the case of an area of small polygons, a few examples of polygons with upturned margins were noted (Fig. 4). In some instances the reverse curvature was noted, the margins of the polygons curving down ½ inch or a little more.

The observations made at Miami and Key West appear to indicate that absolute uniformity does not prevail in the behavior of saline mud cracks with reference to curling. In the great

[1] *Op. cit.*, p. 143.

majority of cases, however, the surface layers of the polygons either remain flat or warp down at the margins. The downcurling appears to be general only when the thickness of the mud is very slight as in the cases observed at Key West.

RIPPLE MARKS

With few exceptions the published observations on ripple marks of recent deposits relate to quartz sand ripple marks. In subtropical

FIG. 4.—Calcareous mud cracks with small polygons showing in some cases polygons with margins slightly upcurved; Miami, Florida.

and equatorial latitudes, calcareous sand frequently entirely supplants quartz sand on the beaches and in near shore waters. The specific gravity of the two kinds of sand is essentially the same and they react to wave and current action in much the same way.

It may be profitable to describe briefly the conditions under which ripple marks are now being impressed on calcareous sediments or potential limestones at certain localities in the Florida-Bahama region easily accessible from main routes of travel.

The waters adjacent to Providence Island in the Bahamas afford good opportunities to see ripple marks on calcareous sand at certain localities near the city of Nassau. The channel between

Hog Island and Providence Island, which generally has a depth of from 1 to 3 fathoms, furnishes conditions favorable to the development of tidal currents of varying velocities between Nassau and the reefs of living corals 4 miles east. The currents are strong enough near the corals to keep the limestone bottom to which they are attached swept clean of calcareous sand.

Between the reefs and the east end of Hog Island, considerable stretches of the bottom are covered with white sand on which numerous patches of "sea grass" are growing, which partially or entirely prevents the development of ripple marks. Farther west where the "grass" is absent the white sand, consisting largely of coarse, shell fragments, is marked by ripple marks with short wave-length (2 to 4 inches) of the ordinary current-mark pattern (see photograph by Kindle).[1] Over the easterly part of the white sand bottom, where the currents probably have their maximum strength, the bottom is covered with sand waves or metaripples.[2] These have a wave-length estimated at from 15 to 20 feet and an amplitude of 6 to 8 inches.

The waters of Biscayne Bay, Florida, furnish a considerable area of white calcareous sand bottom under water sufficiently shallow (12 to 18 feet) to permit careful inspection from a glass-bottomed boat. Much of the bottom between Miami and Cape Florida is covered with marine plants which prevent the occurrence of ripple marks. Near the Cape, however, waves and currents have kept the bottom free from plant colonies. Asymmetric ripple marks with rather long wave-length were observed near Cape Florida. A short distance from the steamer landing on the west side of the Cape parallel ridges of the sand wave type were seen spaced 25 to 50 feet apart. In the deeper water highly irregular bottom features occurred somewhat comparable in complexity of pattern with the flat-topped sand ridges at Annisquam, Massachusetts, illustrated by Kindle.[3]

[1] E. M. Kindle, "Recent and Fossil Ripple Mark," *Can. Geol. Surv., Mus. Bull.* 25 (1917), Plate VII.

[2] W. H. Bucher, "On Ripples and Related Sedimentary Surface Forms and Their Paleogeographic Interpretation, Parts I and II," *Amer. Jour. Sci.*, Vol. XLVII (March–April, 1919), p. 181.

[3] *Op. cit.*

So far as can be judged from the literature, fossil limestone ripple marks generally show a wave-length of from 1 to 5 feet. The widely spaced ripples with a wave-length of 15 feet or more, which appear to be very common on the calcareous sand of the Bahama-Florida regions, do not seem to have been noted in limestones. Ripples with a wave-length of only 2 or 3 inches appear likewise to have generally escaped the notice of geologists. This apparent discrepancy between the size of the ripple marks of limestone and that of calcareous sea bottom will probably disappear when search for such features becomes more thorough.

Ripple marks of unmistakable current-ripple type with a wave-length of $1\frac{1}{4}$ inches and amplitude of $\frac{1}{8}$ inch are represented in the Canadian Geological Survey collection by a specimen from the Upper Devonian limestone of the Hay River section, North West Territory, collected by Mr. E. J. Whittaker. No other example of ripple marks of equally or comparably small wave-length in limestone has come under the notice of the author although symmetrical ripple marks of similar wave-length and amplitude in sandstone are very common.

Miller[1] states that small ripple marks with a wave-length of from 1 to 2 inches and amplitude of $\frac{1}{2}$ inch occur at several horizons in the Pamelia, Lowville, and Trenton, but does not indicate whether they are current or oscillation ripples.

The numerous examples of Palaeozoic limestone ripple marks described by Prosser include both symmetrical and asymmetrical ripples but all are forms with long wave-length, generally from 20 to 36 inches. In several cases they are described as "clearly asymmetrical,"[2] or with slopes steeper to the west than to the east. thus leaving no question as to their current origin. In other cases Prosser found "no difference in the slope." Udden[3] notes limestone ripples which are "slightly unsymmetrical."

[1] William J. Miller, "Geology of the Port Leyden Quadrangle, Lewis County, N.Y.," *Bull. N.Y. State Mus., No. 135* (1910), p. 36.

[2] Charles S. Prosser, "Ripple Marks in Ohio Limestones," *Jour. Geol.*, Vol. XXIV, No. 5 (July–August, 1916), p. 459.

[3] J. A. Udden, "Notes on Ripple Marks," *ibid.*, No. 2 (February–March, 1916), p. 125.

Bucher[1] has brought together measurements of a number of limestone ripples with large wave-lengths which are "nearly symmetrical," and has raised the question whether the formation of such large ripple marks by wave action is possible.[2] He writes, "Since a neutral name is desired for the large, nearly or completely symmetrical ripples showing no assortment of grain, I suggest the term 'pararipples.'"[3]

The writer considers the pararipples to represent metaripples sufficiently modified either by wave action or reversed tidal currents to have lost their original asymmetry.

The association of mud cracks with limestone ripple marks having a wave-length of 2 feet in the Ordovician of southeastern Indiana, reported by Shannon,[4] would be significant in this connection if it should be found that they are symmetrical. Ripple marks 2 feet from crest to crest certainly could not have been formed by wave action in water shallow enough to permit the formation of mud cracks at low tide.

Limestone ripple marks of large amplitude have sometimes been inferred to represent water of considerable depth.[5] The writer's observations on the large ripples, now being formed in the shallow waters of the Bahamas, on calcareous sediments have convinced him that no trustworthy conclusion regarding the depth can be drawn unless the ripples can be shown to be of the oscillation type. The widely spaced ripple marks frequently met with in limestones have probably been in nearly all cases formed by currents. Since the wave-length and amplitude of current ripples depends chiefly upon the velocity of the current, and not at all upon depth, no reliable deductions regarding the latter can be drawn from them.

[1] *Op. cit.*, p. 260.

[2] *Ibid.*, p. 262. [3] *Ibid.*, p. 263.

[4] "Wave-Marks on Cincinnati Limestone," *Proc. Ind. Acad. Sci.* (1894–95), pp. 53–54.

[5] J. Locke, "Professor Locke's Geological Report," *Ohio Geol. Surv., Second Ann. Rept.* (1838), p. 247, Plate 6.

ALGAE, BELIEVED TO BE ARCHEAN

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During recent years attention has been called to the widespread occurrence of fossils in Huronian rocks.[2] These fossils are mainly algae, although bacteria,[3] including iron bacteria,[4] have been found. The work on the origin of the iron-bearing formations of northeastern Minnesota led the writer to a close examination, not only of the Huronian cherts, but also of the Archean Soudan formation and the overlying conglomerates.[5] The discovery of micro-organisms in chert pebbles at the base of the Pokegama quartzite (Upper Huronian) of the Mesabi range[6] encouraged the search for organisms in still older conglomerates. This resulted in the finding of fossil algae in pebbles of the Ogishke conglomerate.

The Ogishke conglomerate is the lowest formation of Huronian age north of Lake Superior, and overlies directly the Archean basement complex. It is highly folded and metamorphosed. The pebbles in it include all the varieties of rocks found in the Archean

[1] Published by permission of Dr. W. H. Emmons, director, Minnesota Geological Survey.

[2] C. D. Walcott, "Pre-Cambrian Algonkian Algal Flora," *Smiths. Inst. Misc. Coll.*, Vol. LXIV, No. 2, 1914; *ibid.*, "Notes on Fossils from Limestone of Steeprock Lake, Ontario," *Geol. Surv. Canada, Mem. 28*, 1912, p. 16; E. S. Moore, "The Iron Formation on Belcher Islands, Hudson Bay, etc.," *Jour. Geol.*, Vol. XXIV (1918), pp. 412–38; Grout and Broderick, "Organic Structures in the Biwabik Iron-bearing Formation of the Huronian in Minnesota," *Amer. Jour. Sci.*, Vol. XLVIII (1919), p. 199.

[3] C. D. Walcott, "Discovery of Algonkian Bacteria," *Proc. Nat. Acad. Sci.*, Vol. I, (1915), p. 256.

[4] J. W. Gruner, "The Origin of Sedimentary Iron Formations: The Biwabik Formation of the Mesabi Range," *Econ. Geol.*, Vol. XVII (1922), p. 418.

[5] N. H. Winchell, "Geology of Minnesota," *Geol. Nat. Hist. Surv.*, Vol. IV (1899), p. 282; J. M. Clements, "The Vermilion Iron-bearing District of Minnesota," *U.S. Geol. Surv., Mon. 45*, 1903, p. 274; C. R. Van Hise and C. K. Leith, "The Geology of the Lake Superior Region," *U.S. Geol. Surv., Mon. 52*, 1911, p. 129.

[6] J. W. Gruner, *op. cit.*, p. 420.

beneath it. In some places greenstone pebbles predominate; in others, granitic ones, while in some areas chert pebbles, associated with red jasper pebbles, are abundant. Most of them are subangular though well worn, and as a rule they do not exceed 2 inches in diameter. Their chert and jasper cannot be distinguished from that of the Soudan formation. Even the finely banded structure so common in the Soudan formation is frequently found in the pebbles. There seems, however, to be a slight difference in the size of the grain of the Soudan chert found in place and that found in the pebbles. It is the opinion of the writer that the pressure on the chert pebbles was diverted to some extent by the yielding of the more or less heterogeneous and possibly still porous matrix around them. The chert pebbles, being the hardest and simplest in chemical composition, emerged from metamorphism without apparent change, while greenstone pebbles were elongated in many instances. This reasoning led to the original microscopic examination of pebbles.

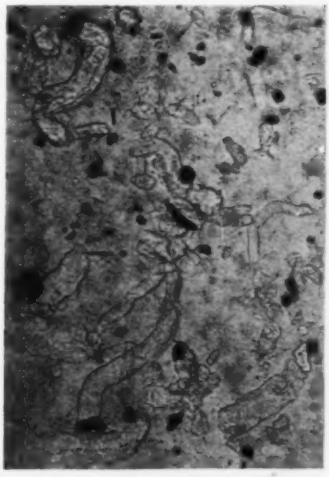

FIG. 1.—Blue-green algae. (Slide M 1053 D.) *Inactis* or *Microcoleus*. ×190.

FIG. 2.—Tracing of alga with canal. The same slide as in Figure 1. ×400.

The pebbles examined were dug with difficulty out of apparently glaciated rock surfaces on a number of islands in Ogishke Muncie Lake. Some were collected from the outcrops on the north shore of the lake. The two pebbles which contain the algae (Figs. 1, 2, and 3) come from an island in the S.W. $\frac{1}{4}$, Sec. 23, T. 65 N., R. 6 W. The pebbles are gray in color. The fossils consist of carbonate, the exact nature of which cannot be determined without risking the slides. The

matrix of the organisms is a very fine-grained chert containing many minute needles of brownish amphibole, very small crystals of carbonate of the same kind as that of the fossils, some magnetite, and minute specks of pyrite. This is exactly the composition of the chert of the Soudan formation in place. The latter, however, is slightly more recrystallized.

For the identification of the fossils the writer is indebted to Professor Josephine Tilden, algologist at the University of Minnesota. Professor Tilden classes them as blue-green algae corresponding to such types as *Inactis* or *Microcoleus*. Some of the structures which represent the sheaths of the plants show the "canals" in which the algae proper lived. Figure 2 is a tracing (taken from a photograph) of such a sheath, showing the "canal."

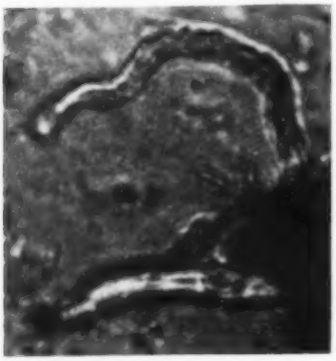

FIG. 3.—Blue-green algae. (Slide M 931 B.) ×2,200.

Since the publication of the paper on the origin of the Biwabik iron-bearing formation,[1] more algae of Huronian age have been discovered in chert of the same kind and from the same locality as that which contains the iron bacteria. The algae consist of chert, or are replaced by some brownish or greenish iron-containing mineral. Figure 3 is a highly magnified (×2,200) view of one of these organisms which, according to Professor Tilden, also belong to the blue-green algae of the type *Inactis* or *Microcoleus*. They are so small and inconspicuous at a magnification of less than 100 diameters that they escape attention. It is not improbable, therefore, that examination of rocks with this purpose in view will reveal fossils previously overlooked on account of their extremely small size.

In conclusion, the author expresses the belief that the blue-green algae in the chert pebbles of the Ogishke conglomerate are of Archean age, and that algae and bacteria were partly responsible for the deposition of the Soudan formation.

[1] J. W. Gruner, *op. cit.*

AN ASSOCIATION OF KAOLINITE WITH MIAROLITIC STRUCTURE[1]

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While engaged in geologic mapping of the Wrangell district in southeastern Alaska, the writer collected a suite of specimens which seem to illustrate very well one mode of origin of kaolinite, though not the most common one.

The general geology of the occurrence is as follows: A long, narrow stock of granite—possibly 25 miles long and 2 miles wide—extends across Etolin Island in a southeast-northwest direction, and is intrusive into a much larger stock of diorite. On the southeast side of Zarembo Island, farther to the northwest, along the same general line of strike, small stocks and intrusive masses of granite porphyry and rhyolite porphyry are found in slates, and are presumably outlying masses of the main stock. Many small masses of conspicuously miarolitic granite porphyry, intrusive into schists, are also found on the islands of Ernest Sound to the northeast of the main stock. The kaolinite in question occurs as fillings in druses in the rhyolite porphyry, and as an alteration product of the plagioclase feldspars in the granite porphyry of the Etolin Island stock. The rocks examined are in a glaciated region and are fresh and unweathered.

At the southeastern end of the granite stock the rock is a medium-grained pink granite, with a compact granitoid structure. The major component minerals are microcline-microperthite and quartz, with about 10 per cent or more of albite-oligoclase, a little hornblende and biotite, and accessory zircons and magnetite. About 12 miles northwest, the rock has changed to a pink granite porphyry with granophyric ground-mass and a prominent miarolitic structure. The druses average about one-half centimeter in diameter, and are

[1] Published by permission of the Director, United States Geological Survey.

lined with terminated quartz crystals and well-bounded crystals of microperthite projecting into the cavity. In the miarolitic cavities of the granite porphyry masses of Ernest Sound, hexagonal biotite crystals are common in addition to the quartz and feldspar. About 12 miles farther to the northwest, on Zarembo Island, are the small masses of white rhyolite porphyry intrusive into slates. The rhyolite porphyry is exceptionally miarolitic, and the volume of the druses, as measured on the polished surface of a hand specimen, is about $4\frac{1}{2}$ per cent. The druses vary from the fraction of a centimeter to a centimeter in diameter. These druses are lined with terminated quartz crystals projecting into the cavity, and are associated or flecked with many small plates of crystalline hematite (specularite). The druses are further partially or completely filled with a microcrystalline granular aggregate of kaolinite (Av. $n = 1.564 \pm .003$), and the central portion is usually filled with calcite. In some specimens kaolinite is absent and calcite alone fills the central portion.

If we consider the texture of the different facies of the rock to indicate the physical conditions during consolidation, an interesting correlation may be made between these conditions and the miarolitic structure and mineral association of the druses. The medium-grained granite with only a faint trace of porphyritic texture is compact, and presumably cooled so slowly that opportunity was given for the mineralizers in solution to escape gradually. The granite porphyry may be considered to have suffered an abrupt change in its rate of cooling, probably accompanied by increased viscosity, so that either the released gases or residual fluid were in part temporarily trapped, and deposited the pneumatolytic minerals in the druses. The mineral association of the druses—quartz, microperthite, and biotite—is characteristic of high temperature and pressure. The rhyolite porphyry represents a still more abrupt change in rate of cooling and a lower drop in temperature. The abrupt crystallization attendant upon this may have resulted in an increased vapor pressure, resulting in larger and more prominent druses than in the granite porphyry. The mineral association of the druses—quartz and specularite—is one such as is found in the early stages of the formation of zeolites in surface flows.

The kaolinite and calcite were deposited in the druses of the rhyolite porphyry still later than the quartz-specularite combination, and hence probably at still lower temperatures under hydrothermal conditions. The possible source and origin of the kaolinite is indicated by certain phenomena found in the granite porphyry now exposed at the surface. The plagioclase feldspars of this rock are zoned, and the more basic cores of many of them have been altered to fibrous kaolinite, which has been partially or completely removed so that many of the plagioclases show cavities and pits with an etched solution surface, whereas others are still partially filled with a porous kaolinitized feldspar residue. It was impossible to isolate the crystalline fibers to prove whether they were sericite or kaolinite, but the porous character suggests the latter. It is reasonable to assume that the rhyolite porphyry passes transitionally downward into a granite porphyry similar to that just described, and that the kaolinite and calcite in the druses of the rhyolite porphyry have been derived through the partial alteration and leaching of the plagioclase feldspars of such an underlying granite porphyry by thermal carbonated waters of relatively low temperature. This conclusion is in line with the latter part of the statement of Lindgren[1] "In brief, kaolin is never a high temperature mineral but is either a product of alteration by descending waters containing sulphuric acid of carbon dioxide, or of alteration by ascending weak carbonated waters close to the surface."

[1] W. Lindgren, "The Origin of Kaolin," *Econ. Geol.*, Vol. X (1915), p. 90.

EDITORIAL

AN ANCIENT THEORY OF THE PACIFIC

Away back in the last century a wit of Washington noticed that two tall blonde geologists were much together on the streets, that they looked somewhat alike, and were obviously very fond of one another; so he dubbed them "The two Dromios." It "took"—even with the victims. They tried to settle between themselves which was the Dromio of Ephesus and which was the other Dromio; but it was too much for them. So they fell to calling one another simply "The Other Dromio." This was really an improvement on Shakespeare. "The Other Dromio" and "The Other Dromio" were as alike as two peas, as everyone must admit. So thenceforward their letters to one another had the same signature and the last letter that passed between them was signed "The Other Dromio."

Now once upon a time, away back in the last century, these two Dromios were together in the field, and after a long tramp they sat down to rest. Said one Dromio to his mate, "Do you want to know my theory of the Pacific?"

"Certainly," said The Other Dromio, "fire away!"

"Well, sir, in the first place the Moon was pulled out of the west-southwest side of the Earth. In doing this the east side of the crust was badly cracked up. A great zizag crack ran down the west side of Europe and Africa. Europe itself was cracked all to pieces, and stray cracks ran off into Asia and Africa. Europe, as we all know, remains sadly cracked even unto this day.

"The pieces of crust on the west side of the great zigzag crack pushed off as far as they could and have ever since tried to keep out of world-rumpuses of this and all other sorts. This is the gist of my theory of the Pacific Basin and of the Atlantic also." And then he laughed a laugh that scared away the birds.

Then The Other Dromio rose right up and said: "Let's move on."

None the less, he told the story over and over again for years afterward to the boys to whom he lectured, as a clever way to keep them in mind of some of the freak features of the globe.

But the story lost flavor when it was found that the fission theory could not be made to fit the case of the earth and moon (*Carnegie Publication No. 107* (1909), pp. 77–160; summarized on pp. 127–33 and 158–60); and it was dropped. We learn, however, that it has broken out again in a new and virulent form in the land that is alleged to have been most queered by the original catastrophy.

THE OTHER DROMIO

REVIEWS

The Friendly Arctic. By VILHJALMUR STEFANSSON. (With a Foreword by GILBERT GROSVENOR, President of the National Geographic Society, and an Introduction by Rt. Hon. SIR ROBERT BORDEN, Prime Minister of Canada.) Macmillan, 1922. Pp. xxx+784, illustrated.

When the explorer Nansen made the "Fram" fast to an ice floe near the New Siberian Islands and began his zigzagging four years' drift across the northern polar sea, he was pinning his faith to a simple but convincing deduction from observed fact. This was the finding on the west coast of Greenland of driftwood derived from the "Jeannette" which had been crushed in the ice four years before near these islands, so that the course of the driftwood must have been in the pack itself across the frozen sea. The result of his adventure was a splendid vindication of his scientific reasoning, with which, however, those of his colleagues familiar with the facts generally concurred, even though unwilling to stake their lives and their scientific reputations upon it.

Stefansson when he introduced into polar exploration an entirely new method, launching himself boldly out upon the apparently barren Beaufort Sea without adequate supplies and with the necessity of later finding his means of sustenance in the sea itself, he was by so doing setting his own judgment squarely against that of practically all other scientists as well as arctic explorers, and the gauges which he threw down were his life and his scientific reputation. The best proof that his method was believed impracticable is that when nothing was heard from him he was so generally given up for dead.

The Friendly Arctic, in which the account of the latest arctic expedition is now given to the world, is an attempt by this ultra-modest explorer to convince his readers that his achievements were commonplace and required nothing of the extraordinary or heroic; but in spite of this the book is one of the most romantic and gripping to be found in the whole field of arctic adventure, and it has been listed among the best sellers during the summer season. Throughout its nearly 800 pages, the interest never for a moment flags, and one lays down the book feeling that he has come into intimate contact with a remarkable though very human

personality. The book is in reality an autobiography, for in his attempts to put before his readers what he regards as the genial atmosphere of this northern wilderness, he has sought to do it through his own physical, mental, and emotional reactions. In the long list of polar explorers one finds but rarely a man of scientific training. Stefansson is an exception, and the technique of his expedition is throughout an application of modern science quite unhampered by the elaborate conventions of our modern social system. This applies with special force to the vitally important items of diet, shelter, and clothing.

Among the noteworthy achievements of the expedition are included the making known of about 100,000 square miles of the hitherto unknown Arctic, the discovery of three large and a considerable number of smaller land bodies all north of 73° N. latitude; the careful mapping of over 600 miles of new coast line and the correction of the coast lines, the positions and even the character of some of the land areas discovered by Sverdrup; the making of over sixty soundings in widely separated and generally newly discovered portions of the Arctic Ocean; the confirmation of the non-existence of Crockerland; the discovery of a number of coal (lignite) deposits upon the islands of the arctic archipelago; and, especially by the southern party, large collections to show the zoölogy and the botany of the northern coast regions of the continent.

These achievements are the more remarkable by reason of the crushing disaster which almost at the outset overtook the expedition in the loss of the "Karluk," the principal ship of the expedition, together with the major part of its equipment; and perhaps even more important and serious the mutinous behavior of the second in command of the expedition, who was in charge of the southern party, and of others under him. The reviewer is writing this after the case for the mutineers has been stated (in *Science* for July 7, 1922), in which the attempt is further made to show that Stefansson's exploring methods are not new and can be made use of only within extremely limited and favorable districts and for limited seasons only of the year. But it should be clear that the earlier explorers, Rae and Hanbury, who have been cited as sustaining themselves upon the country, both lived in the neighborhood of the coasts, and Stefansson throughout his book has been at much pains to make clear that for the winter season when the light is insufficient for successful hunting, the food must be secured earlier in the season. Likewise, the hides for the clothing and especially for the water-tight boots must be secured at the favorable season.

Lest there should be misunderstanding, Stefansson has stated his case most concisely (p. 5):

> Now if it could be demonstrated that food suitable to sustain indefinitely both men and dogs could be secured *anywhere in the polar sea* [italics are mine] then obviously journeys over the ice would cease to be limited either in time or distance. Any part of the polar sea would then become accessible to whoever was willing to undergo the supposed hardships of living on meat exclusively, using nothing but blubber for fuel, and remaining separated from other human beings than his own traveling companions for a period of years.
>
> To demonstrate the feasibility of this . . . . was the main task of our expedition.

We think Mr. Jenness' criticisms along this line may be set at rest by the statement of Admiral Peary, made in the last public address before his death, when, in presenting Stefansson to the members of the National Geographic Society for the award of the Hubbard Gold Medal, he said: "Stefansson has evolved a way to make himself absolutely self-sustaining. He could have lived in the Arctic fifteen and one-half years just as easily as five and one-half years. By combining great natural, physical, and mental ability he has made an absolute record." This statement is to be weighed as not only that of the greatest of polar explorers, but one the plan and technique of whose sledge journeys has been based on the notion that food was unobtainable on the frozen sea way from the coasts.

Stefansson's expedition, officially known as the Canadian Arctic Expedition, carried probably the most elaborate outfit and scientific personnel of any that has ever gone to the arctic. It sailed originally in two ships, the "Karluk" for the geographic (exploring) work, and the "Alaska" for the more detailed scientific work of the southern party in the neighborhood of Coronation Gulf. Later the small vessels "Mary Sachs" and "North Star" were purchased for special work. The expedition was fortunate in having the intimate and cordial personal interest of the Prime Minister of Canada, Sir Robert Borden, who has supported the commander of the expedition in all the trying incidents which developed. In the introduction to *The Friendly Arctic*, written in October, 1921, he says:

> The results accomplished by this expedition would have been impossible if Stefansson had been a man of less resource and courage. His commanding intellectual powers, remarkable faculty of observation, capacity for keen analysis of facts and conditions, splendid poise and balance, and immense physical strength and endurance made great results possible. . . . . The thanks and appreciation of the Canadian Government have been conveyed to him in a Minute of Council.

With the "Karluk" were carried off most of the sounding apparatus, the sledge chronometers, and the men of especially adventurous

disposition, as well as the better sledges and dogs. The mutiny led by the second in command, which had culminated at Collinson Point, made the preparations for the initial ice trip across the Beaufort Sea several weeks late in starting, and it was this trip which was to test out the plan of the commander. When about to start, a gale of exceptional severity intervened and further held up the departure until the season was so late as to render the expedition hazardous. Shortly after starting out on March 22, 1914, one of the men was severely wounded by a fall and had to be taken back; then two of the best men together with the best dogs who had been sent back with sledge loads but were to rejoin the expedition, were unable to do so owing to a gale and consequent drift of the floes; yet after ninety-three days on the ice the little party of three men made a landing on Banks Island after having traveled about 700 miles over the ice floes and conclusively demonstrated the theory of exploration in the arctic which Stefansson had so persistently advocated in the face of universal opposition. This method was to have many other demonstrations during the more than five years that the expedition remained in the arctic.

Yet a careful reading of this and other parts of the narrative leaves one in little doubt that it is only the exceptional man trained in the technique of seal-hunting and one content to adapt himself to the all-meat diet, who can carry out such an expedition successfully. He must be ready at times to crawl over the floes for hours, lying all the time in ice-cold water in order to stalk the seals necessary for his sustenance, and when on land he must be ready to hunt continuously perhaps for as many days before securing the necessary caribou. In the opinion of the reviewer, Stefansson, in the effort to prove to his readers the friendliness of the arctic to the explorer, has made them see the necessary hardships through his own eyes, those of a quite exceptional shot with the rifle and today the most experienced living craftsman in the technique of arctic travel. His "residence" in the arctic now exceeds that even of Peary, and his continuous "residence" does also. None the less it is true that he has dispelled many illusions quite generally held and has proved the habitability of the northern "barrens" of British America, where a great industry may be developed in meat supply from reindeer and perhaps other herds. The map of the sledge-journeys indicates pretty clearly that the last land masses of the arctic archipelego have now been charted.

A very valuable contribution to our knowledge which has resulted from Stefansson's expedition is the means of preventing or of curing

scurvy, which for a long time was the greatest handicap to polar exploration. Quite contrary to the general view, Stefansson has shown that the antiscorbutic value of certain foods does not lie in their composition, but only in their freshness. Almost any fresh food is an antidote for scurvy, though raw or underdone meat is the most effective. Scurvy is avoided altogether through use of the all-meat diet adopted for the Stefansson expedition.

The book is remarkable well gotten up and is notably free from typographical and other errors. A trifling error is found on page 137, where, in referring to Peary's North Pole sledge-journey, the explorer is made to start from Cape Thomas Hubbard instead of from Cape Columbia. The illustrations are all from photographs but in contrast to most popular accounts of polar adventure, it is the commander only of whom no picture appears.

Whether dealing with the question of scurvy prevention or the technique of snow-house building, of how to stalk the seals or to secure for the larder all the animals in a herd of caribou, the explorer's personality, his scientific methods of thought, his apt illustrations, and his clear and incisive literary style, make the reading of the book fascinating as are few others known to the reviewer. A scrupulous care to do full justice to his subordinates will certainly impress itself upon the reader. If through the accidents of the campaign a sailor in the party has been favored by first sight of a new land, this fact is noted, not only in the diary and in the book, but also in the deposits in the cairns made for future travelers, and in these deposited records the names of all are included.

In the belief of Stefansson these northern lands are destined to have great strategic value as landing stations in the aeroplane routes which in the near future are to connect up the eastern with the western hemispheres across the Arctic Ocean. To many this will appear fantastic, but in an article which has recently appeared in the *National Geographic Magazine* Stefansson appears to have demonstrated the entire feasibility of these routes, and it is easy to see that they must exercise a dominating influence upon the transportation of the future.

WILLIAM HERBERT HOBBS

Annual Progress Report of the Geological Survey of Western Australia for the Year 1921. Perth, 1922.

Pages 1 to 10 give an outline of the work of the Geological Survey since 1896. The remainder of the report (pp. 11–61) deals with the field and office work for the year 1921.

A brief résumé is given of the publications of the Geological Survey, which consist of twenty-five annual reports and eighty-three bulletins. Under the heading "Economic Geology and Ore Deposits," the present condition of knowledge relating to the economic geology of the state is summarized. One of the concrete results of a quarter of a century's work is a geological sketch map of nearly the whole of the state, summing up graphically the work of the survey up to the date of publication, 1920.

The ore deposits of the country are reviewed briefly under individual headings: copper, lead, tin, etc. Aside from gold which, as is well known, has been for many years the greatest mining product of Western Australia, the most important of these appear to be the iron ores, notwithstanding the fact that up to the present their exploitation has been very limited. They are of all grades and of wide distribution. The most noteworthy of the high-grade deposits are those of Yampi Sound, Kimberley division. There are 97,300,000 tons of ore available, two samples of which were found on analysis to contain 65 and 66.5 per cent metallic iron respectively. The close proximity of this deposit to the sea is greatly in favor of its development as a commercial project.

Another important iron ore deposit is that at Wilgie Mia which is almost pure hematite. Analyses of three samples give 68.37, 64.36, and 68.83 per cent metallic iron respectively. There are 27,000,000 tons of ore in sight above the level of the plain and according to borings the ore continues to a depth of 250 feet in places with no appreciable diminution in quality. This deposit is within 40 miles of a railway, and about 200 miles from Geraldton, which is a seaport. Both the Yampi Sound and the Wilgie Mia ores are very low in phosphorus and sulphur and contain only traces of titanium.

Other ores of importance in steel manufacture, namely those of manganese, tungsten, and molybdenum, are present in commercial quantities.

Coals of different geologic ages are known, but mining has been carried on extensively in only one district, the Collie Coalfield, from which 5,000,000 tons have been raised. The coals of the Collie field are subbituminous, non-coking coals, which approach very closely to lignite in some parts. The principal consumer has been the railways department. About 10 per cent of the production has been used as bunker coal. The other known coal deposits are chiefly of lower grade. Considerable search for coal has been carried on in the extensive areas of Permo-Carboniferous rocks but unfortunately it has proved fruitless. Apparently the future industrial development of Western Australia is handicapped by scarcity of high-rank coals.

Commercial deposits are known of many of the minor non-metallic minerals but as yet there has been little production. Great interest has been taken in Western Australia in the world-wide search for petroleum but so far there has been no noteworthy development. Two asbestos deposits are described. Chrysotile asbestos of good quality is found at a number of localities over a distance of 200 miles. The fiber compares favorably with that found in any other part of the world with the possible exception of the best Canadian, and although the veins are small the high quality makes it probable that important development will take place.

Under the heading "Some Problems Awaiting Solution," the future work of the Survey is discussed. Among others, the following statement is significant:

> A more thorough investigation than has yet been found possible into those multifarious petrological problems which have such an intimate bearing upon the genesis of the ore deposits of the State, and the conditions which govern their deposition and to a certain degree control the distribution, extent and value of the mineral deposits.

The officers of the Geological Survey of West Australia have done much valuable work in the past and their future contributions to the science will be looked for with keen interest by their brother geologists in other parts of the world.

A. H. B.

Guide Book of the Western United States, Part E. The Denver and Rio Grande Western Route. By MARIUS R. CAMPBELL. Bulletin 707, U.S. Geological Survey, Washington, D.C. Pp. 266, pls. 96, figs. 63, maps 10.

There has recently appeared the fifth part of the well-known *Guide Book of the Western United States* which the U.S. Geological Survey inaugurated at the time of the San Francisco Exposition in 1915. This latest guide, which follows the plan adopted in the earlier bulletins of the series, describes the scenery and treats of the geology of one of the most scenic of the western railway routes. In addition to treating of the tracts immediately adjoining the Denver and Rio Grande Western Railroad between Denver and Salt Lake City, it includes a number of one-day trips that may be made to points of interest from Denver, Colorado Springs, Cañon City, and Salt Lake City.

The book contains a fund of interesting and useful information and is elaborately illustrated with shaded relief maps, halftone plates, diagrams and sections. To the geologist it will prove of value either while traveling by the Denver and Rio Grande, or as a convenient reference book wherein is summarized much of the geology of these portions of Colorado and Utah.

It may be obtained for one dollar from the Superintendent of Documents, Washington, D.C.

R. T. C.

The Shapes of Pebbles. By CHESTER K. WENTWORTH. Bulletin 730 C, U.S. Geological Survey, 1922. Pp. 24, pls. 2, figs. 17. Contains two separate papers entitled "A Method of Measuring and Plotting the Shapes of Pebbles" and "A Field Study of the Shapes of River Pebbles."

The writer of the above papers shows clear appreciation of the importance of the quantitative elements in geology. Such efforts as these are gradually lifting the "study of earth features" from a purely descriptive account to a truly measurable science.

The first of these two papers is essentially an account of the methods employed in determining curvatures of pebbles. Two terms are introduced, (1) the "roundness ratio," or the ratio of the radius of curvature of the sharpest "developed" or secondary edge to the main radius of the pebble, and (2) the "flatness ratio," or the ratio of the radius of curvature in the most convex direction of the flattest "developed" face to the mean radius of the pebble. The measurements are made with a cleverly modified optical convexity gage. The results for each pebble are plotted on logarithmic co-ordinates, applying the "roundness ratio" as ordinate and the "flatness ratio" as abscissa; perfect spheres would thus lie near the upper left corner, angular pieces with reduced facets toward the lower left corner, and pebbles with nearly plane facets toward the lower right corner.

A number of pebbles of different origins (glacial, sandblasted, and river-worn) were thus plotted and the writer was enabled to establish clearly a distinctive grouping with boundary lines for each of these types. There is a slight overlap of glacial and river pebbles, but glacial and sandblasted pebbles are quite distinct. It thus appears that a fairly ready method is available for classifying sediments of large-diameter particles and of uncertain origin. A large number of measurements are

required to secure satisfactory results. The reviewer is interested in seeing what the writer will be able to do along similar lines with regard to that anomaly in form-classification schemes, lake-shingle. It also appears questionable whether, in view of the fact that protuberances are more rapidly worn away in softer rocks, the scheme will not have to be somewhat modified to fit smaller pebbles of softer material.

This very point is, to some extent, met with in the second paper, which is a concrete study of the ratios suggested and the distances traveled by the pebbles. After locating a distinctive bed of quartzite which outcropped in a stream valley, more than 600 pebbles from this bed were collected at intervals downstream from the outcrop. Mileage traveled was plotted against "roundness ratio" for each pebble. For compiling these data the unknown hardness factor, which varied with each pebble, had to be ignored. It was found, however, that the roundness ratio is proportional to the linear size of the pebbles.

After the application of various corrections, the resulting curve was compared with that obtained by "artificial erosion" of pebbles in a motor-driven, water-filled, rotation barrel. It was found that the two corresponded fairly closely.

It seems, then, that the degree of rounding of pebbles may be accepted as a fairly satisfactory means of estimating the distance which this material has traveled. The careful writer points out several minor vitiations of this principle and the reviewer recognizes that these are of importance in the immediate and practical application of the methods here outlined. But he holds that the general scheme outlined above is the clue to much that is yet unsolved in the origin of certain conglomerates and erratics. The Geological Survey is to be commended for aiding such work as is presented in this paper.

C. H. Behre, Jr.

Lehigh University

An Introduction to the Geology of New South Wales. By C. A. Süssmilch. Third edition, revised and enlarged. Pp. 281, figs. 92, tables 5, and folded geological map. Angus & Robertson, Sydney, 1922.

The third edition of this very excellent and useful work has now appeared, eight years after the appearance of the second edition. The principal changes will be found in the chapter on the Carboniferous period, to which notable additions have been made. The Carboniferous

strata of New South Wales are now divided into a lower division of marine origin (Burindi series) and an upper division of terrestrial origin (Kuttung series). In the area immediately north of the Lower Hunter River district these have a total thickness of 14,200 feet. Of especial significance are the glacial tillites and varve shales in the upper portion of the Kuttung series. At least three periods of tillite deposition occurred in the Seaham district; these are separated from one another by two relatively interglacial epochs during which varve shales were deposited in lakes along the margin of an extensive ice front. Further study is bringing to light the fact that the Australian glaciation near the close of the Paleozoic was not confined to the Permo-Carboniferous period, as that is now defined in Australia, but occurred also in the Carboniferous. In the second edition of this work, no mention was made of glaciation in the Carboniferous period.

Following the Carboniferous is the very remarkable Permo-Carboniferous period which presents so many problems of extraordinary interest in Australia. Attaining a maximum thickness of 17,700 feet in New South Wales, the Permo-Carboniferous strata comprise an unusual alternation of thick marine series, extensive coal measures, and glacial beds. This period rightly enough has received more extended treatment than any other.

The book is well printed and well illustrated and gives in concise form just what one wishes to know.

R. T. C.

The Rift Valleys and the Geology of East Africa. By J. W. GREGORY. Pp. 479, pls. 20, figs. 44. Seeley, Service & Co., Ltd., London, 1921.

In this work Professor Gregory has assembled much of what is known of the geology of a very significant portion of the African continent. As the title indicates, the outstanding feature is the Great Rift Valley, or zones of rifting, in which essentially parallel fracturing has taken place on a vast scale. In East Africa the main fault trench, about 40 miles wide, is bordered by prominent boundary faults which in some places form steep single scarps and in some other places cause a succession of steps. On the floor of the trench a great number of lesser faults run nearly north and south approximately parallel to the master bordering fractures. Lakes abound on the floor of the trench.

The chief value of the book in the opinion of the reviewer lies in its descriptive geology, for one may well receive the assigned cause of the

rifting and its relation to contemporary earth movements with reservation. At the end is a valuable bibliography amounting to thirty pages.

R. T. C.

Notes on the Geology of New Zealand. (To accompany Geological Sketch Maps.) By P. G. MORGAN. *New Zealand Journal of Science and Technology*, Vol. V, No. 1, pp. 46–57. Wellington, N.Z., 1922.

In this article, from the *New Zealand Journal of Science and Technology*, the author has given a brief outline of the areal geology of New Zealand so far as it is known. The geological maps in black and white which the notes are to accompany have been compiled from a number of maps made at different times and by various geologists. The extraordinarily complicated structure and the fact that New Zealand geologists have differed greatly on vital points have made the task a difficult one. The European time scale has been used to make the maps more intelligible to geologists of other countries, but the New Zealand divisions correspond only roughly with the European divisions.

Certain schists, gneisses, and limestones in the South Island have been considered of Archean age but contain intrusives which may be as late as Early Triassic. About one-fifth of the area of the South Island is classed as "undifferentiated and doubtful Paleozoic." There are five small areas known where the strata contain recognizable fossils and the oldest of these faunas is of Lower Ordovician age. Much careful and highly detailed work will be required to make a reasonably accurate map of the Paleozoic strata. The lack of fossils and the intense folding will make this a formidable undertaking. The great and widespread dynamo-metamorphism of certain of these rocks suggests that there were important periods of diastrophism in Pre-Cambrian and Paleozoic times. No Paleozoic rocks have yet been found on the North Island.

Mesozoic rocks are well represented in both the North and South Islands. The early and middle Mesozoic strata fall into one great Trias-Jura series (the Hokanui system). They are all involved in a great post-Jurassic or post-Hokanui deformation. The Middle and Upper Cretaceous strata which follow are separated from those below by a strong and widespread angular unconformity. This unconformity marks by far the greatest break in the known geologic history of New Zealand and had the time scale grown up there instead of in Europe it would

undoubtedly delineate eras rather than periods. Previously the foreshore of Gondwanaland, New Zealand may be said to have begun an independent existence with the post-Hokanui deformation.

There is a stratigraphic and paleontologic break between the Upper Cretaceous and the Tertiary. Tertiary rocks occupy a considerable area on the North Island. The Tertiary periods in New Zealand are noted for their intense vulcanism. The later volcanic rocks contain quartz veins which have yielded many million ounces of gold and silver.

A. H. B.

Phytopaläontologie und Geologie. By DR. W. DEECKE. Berlin: Verlag von Gebrüder Borntraeger, W35, Schöneberger Ufer 12a, 1922. Pp. 97.

Professor Deecke is not a specialist in paleobotany, but writes from a general paleontological point of view. The book summarizes our present knowledge on the geological importance of fossil plants rather than attempting to approach any of these problems on the basis of intimate familiarity with paleobotany.

In spite of this drawback, the book is useful to anybody who wishes a summary of such questions as the importance of marine algae, or the influence of plants on rock formation, or the relative importance of autochthony and allochthony, especially with reference to the formation of coal seams. Another problem, the importance of plants as climatic indicators, has been so much discussed in the last years, that very little can be said about it without constant repetition of familiar ideas.

An interesting chapter is the discussion of plants as index fossils, and Deecke comes to the conclusion that plants are not suitable for a general classification of formations, but rather for the differentiations of horizons in a few periods like the Carboniferous. Plants are especially valuable for index fossils in the determination of local horizons, and have been properly used for such purposes in the Upper Cretaceous and Upper Miocene as well as in the Coal Measures.

Deecke has used extensively the German, Scandinavian, French, English, and American literature. It is only natural that the latter three literatures should not have been fully utilized for the last eight years since, during the war and even after the war, such literature was not always accessible to German scholars, first, on account of their isolation during the hostilities, and afterward, on account of the difficulty of buying foreign literature with devaluated marks.

A. C. Noé

The Upper Cretaceous Gastropods of New Zealand. By O. WILCKENS. New Zealand Department of Mines. Geological Survey Branch. Palaeontological Bulletin No. 9. Wellington, N.Z., 1922.

Die Ursachen der diluvialen Aufschotterung und Erosion. Von W. SOERGEL. Berlin: Gebrüder Borntraeger, 1921. (Price, 18 M.)

Verwertung Geologischer Karten und Profile. Zweite Auflage. Von FR. SCHÖNDORF. Berlin: Gebrüder Borntraeger, 1922.

La Géologie du Pétrole et la Recherche des Gisements Pétroliferes en Algérie. Par MARIUS DALLONI. Alger: Jules Carbonel, Imprimeur Libraire-Éditeur, 1922. (Avec 48 figures dans le texte et une carte.)

Geologic Reconnaissance of the Pidatan Oil Field, Cotabato Province, Mindanao. By WARREN D. SMITH. The *Philippine Journal of Science*, Vol. XX, No. 1. Manila, 1922.

On the Correlation between the Fluvial Deposits of the Lower-Rhine and the Lower-Meuse in the Netherlands and the Glacial Phenomena in the Alps and Scandinavia. By J. VAN BAREN. With 20 plates, 3 sketches, and map. Mededeelingen van de Landbouw-Hoogeschool, Vol. XXIII, No. 1. H. Veenman, Wageningen, 1922.

Review of Philippine Paleontology. By ROY E. DICKERSON. The *Philippine Journal of Science*, Vol. XX, No. 2. Manila, 1922.

Report of the State Geologist on the Mineral Industries and Geology of Vermont, 1919–1920. Pp. 332, pls. 47, figs. 24.

The report comprises a number of papers by various authors on different phases of the geology, and mineral resources and industry of the state. These are:

"The Structural and Metamorphic Geology of the Hanover District, New Hampshire," by J. W. MERRITT: The area studied lies entirely in New Hampshire but is part of a larger area of similar character

extending westward into Vermont. The field work is supplemented by a quantitative chemical and mineralogical study of the schists and granite of the region, leading the author to the conclusion that the schists are of sedimentary origin.

"A Contribution to the Geology of Essex County, Vermont," by ROLF A. SCHROEDER: A study of the occurrence and possible commercial exploitation of the Averill granite as a building stone.

"Notes on the Areal and Structural Geology of a Portion of the Western Flank of the Green Mountain Range," by NELSON C. DALE: An investigation of the more mountainous portions of Middlebury and Burlington Quadrangles, the geology including highly folded and faulted, thoroughly metamorphosed, Cambrian and Pre-Cambrian sediments.

"The Geology and Mineralogy of Braintree, Vermont," by CHARLES H. RICHARDSON and CHARLES K. CABEEN: Of interest is the discovery of new graptolitic beds in the slates of Braintree and Rudolph proving the southward extension of the Memphremagog slates in Braintree and Rudolph to be early Ordovician.

"A Detailed Study of the Trenton Beds of Grand Isle," by GEORGE H. PERKINS, and "A Report on the Fossils of the So-Called Trenton and Utica Beds of Grand Isle, Vermont," by RUDOLPH RUEDEMANN. Professor Perkins describes the distribution and character of the Trenton beds of this locality and calls attention to the fact that the so-called Utica beds present are but a portion of the Trenton. Dr. Ruedemann supplements this paper with a discussion of the paleontology in which faunal comparisons are made with the Trenton of New York and other regions. The limestone he finds to correspond with the Glen Falls division or basal Trenton, of New York, while the black shales are referred to the Canajoharie shale of the same state, and in part also to the Snake Hill division, or Schenectady beds. He comes to the conclusion that the Ordovician is represented in Vermont by beds probably no younger than the Trenton.

"Progress in Talc Production," by ELBRIDGE C. JACOBS: There is an increased demand for talc due to substitution of the domestic material for the foreign product, and increase in the number of uses to which it is put. A complete list of known uses of talc is given, reprinted from a United States Bureau of Mines Bulletin.

"Studies in the Geology of Western Vermont," by CLARENCE E. GORDON: A detailed description of the physiography, stratigraphy, and structure of an extensive area in Western Vermont. A bibliography is appended.

"The Geology of Lake Willoughby," by ELBRIDGE C. JACOBS: Mr. Jacobs concludes that Lake Willoughby is a glacial lake, 1,164 feet above sea level, occupying in part a glacially fashioned trough, which originated probably as a graben. A gorge in the bottom of the lake is believed to be due to glacial cutting. The mountains on either side are composed of Ordovician limestones and phyllites intruded by granite.

"Mineral Resources," by G. H. PERKINS: The author finds that prosperous conditions exist in the mineral industries of the state.

A. C. McF.